

# Adelic geometry on arithmetic surfaces II: completed adeles and idelic Arakelov intersection theory

Weronika Czerniawska          Paolo Dolce

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## Abstract

We work with completed adelic structures on an arithmetic surface and justify that the construction under consideration is compatible with Arakelov geometry. The ring of completed adeles is algebraically and topologically self-dual and fundamental adelic subspaces are self orthogonal with respect to a natural differential pairing. We show that the Arakelov intersection pairing can be lifted to an idelic intersection pairing.

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# 0 Introduction

## 0.1 Background

Adelic theory for global fields was introduced for the first time by Chevalley in the 1930's as a tool for studying the completions of a number field with respect to all possible absolute values at the same time. This is a great expression of "local-to-global" principles as well as an example of geometric approaches to number theory which have proven to be very powerful. One of the principal applications of adelic theory for number fields was published in John Tate's thesis [23] which presented a proof of meromorphic continuation and functional equation of  $\zeta$  functions of number fields in clearer and more compact way than the proof given before by Hecke. When  $C$  is a curve over a perfect field, one can also define the adelic ring  $\mathbf{A}_C$  associated to  $C$  as the restricted product of the complete discrete valuation fields  $K_c$  for any closed point  $c \in C$  with respect to their valuation rings  $\mathcal{O}_c$ . It is possible to obtain a very elegant proof of the Riemann-Roch theorem for curves by using adeles (see [24, 3.] for a sketch of a proof).

Adelic approach has been generalized for higher dimensions by Beilinson in [3] where he defined adelic structures as functors on the category of quasi-coherent sheaves. An explicit theory of 2-dimensional adelic cohomology and dualities for algebraic surfaces was outlined in [20], where hope for proving adelic Riemann-Roch theorem for a surface over a finite field was expressed. However, the explicit adelic structures introduced in [20] are not equivalent to Beilinson's, since [20] worked with objects that now are called rational adeles. The gap on the definitions was partially fixed in [21], but a complete account of 2-dimensional explicit adelic theory was given by Fesenko in [10], where he also proved an adelic Riemann-Roch theorem for an algebraic surface over a perfect field by using properties of adelic cohomology. In particular, Fesenko showed that the function field of an algebraic surface  $X$  can be seen as a discrete subspace inside the ring of 2-dimensional adeles attached to  $X$ . Such a result generalizes the classical result of [23] which shows that a global field is a discrete object inside the ring of adeles.

The non-cohomological part of (explicit) adelic theory for algebraic surfaces can be summarized in the following way: fix a nonsingular algebraic surface  $(X, \mathcal{O}_X)$  over a perfect field  $k$ , then to each "flag"  $x \in y$  made of a closed point  $x$  inside an integral curve  $y \subset X$  we can associate the ring  $K_{x,y}$  which will be a 2-dimensional local field if  $y$  is nonsingular at  $x$ , or a finite product of 2-dimensional local fields if we have a singularity. Note how the geometric dimension of  $X$  matches the "dimension" of the ring  $K_{x,y}$ , and this happens roughly speaking because for a flag  $x \in y$  (assuming that  $x$  is a nonsingular point of  $y$ ) we have two distinct levels of discrete valuations: there is the discrete valuation associated to the containment  $x \in y$  and the discrete valuation associated to  $y \subset X$ .  $K_{x,y}$  is obtained through a process of successive localisations and completions starting with  $\mathcal{O}_{X,x}$  and by the symbol  $\mathcal{O}_{x,y}$  we denote the product of valuation rings inside  $K_{x,y}$ . The step to the global theory is obtained by performing a "double restricted product" of the rings  $K_{x,y}$ : first over all points ranging on a fixed curve and then over all curves in  $X$ , in order to obtain the 2-dimensional adelic ring:

$$\mathbf{A}_X := \prod''_{\substack{x \in y \\ y \subset X}} K_{x,y} \subset \prod_{\substack{x \in y \\ y \subset X}} K_{x,y}.$$

The topology on  $K_{x,y}$  can be defined canonically thanks to the construction by completions and localisations, and by starting with the standard  $\mathfrak{m}_x$ -adic topology on  $\mathcal{O}_{X,x}$ . The topology on  $\mathbf{A}_X$  is obtained after a process of several inductive and projective limits by starting from the local topologies on all  $K_{x,y}$ . In [10] it is shown that  $\mathbf{A}_X$  is self-dual as  $k$ -vector space. For 2-dimensional local fields with the same structure of  $K_{x,y}$  there is a well known theory of differential forms and residues (e.g. [25]); one can globalize the constructions in order to obtain a  $k$ -character  $\xi^\omega : \mathbf{A}_X \rightarrow k$  associated to a rational differential form  $\omega \in \Omega_{k(X)|k}^1$  and the differential pairing:

$$\begin{aligned} d_\omega : \mathbf{A}_X \times \mathbf{A}_X &\rightarrow k \\ (\alpha, \beta) &\mapsto \xi^\omega(\alpha\beta). \end{aligned}$$

Fesenko in [10] proves that the subspace  $\mathbf{A}_X/k(X)^\perp$  is a linearly compact  $k$ -vector space (orthogonal spaces are calculated with respect to  $d_\omega$ ) and the function field  $k(X)$  is discrete in  $\mathbf{A}_X$ . It is possible to define some important subspaces of  $\mathbf{A}_X$  denoted as:  $k(X) = A_0, A_1, A_2, A_{01}, A_{02}, A_{12}, A_{012} = \mathbf{A}_X$  which generate an idelic complex assuming the following form:

$$\mathcal{A}_X^\times : \quad A_0^\times \oplus A_1^\times \oplus A_2^\times \xrightarrow{d_x^0} A_{01}^\times \oplus A_{02}^\times \oplus A_{12}^\times \xrightarrow{d_x^1} A_{012}^\times$$

It can be shown that the space  $\ker(d_X^1)$  is a generalization of the group  $\text{Div}(X)$  since there is a surjective map  $\ker(d_X^1) \rightarrow \text{Div}(X)$  and the intersection pairing on  $\text{Div}(X)$  can be extended to a pairing on  $\ker(d_X^1)$  (cf. [7, 3.]).

The main aim of our work is to obtain a two-dimensional adelic theory, for arithmetic surfaces i.e. objects of the form  $\varphi : X \rightarrow \text{Spec } O_K$  where  $K$  is a number field. The problem is motivated by Fesenko’s “analysis on arithmetic schemes programme”. The programme develops a two-dimensional generalization of Tate’s thesis, i.e. two-dimensional measure, integration and Fourier analysis. Fesenko’s work reveals relationships between geometry and analysis not visible without adelic tools (see also [6] for an alternative presentation).

In [16] and [18] Morrow, develops an explicit approach to residues and dualizing sheaves of arithmetic surfaces. In particular he defines the residue map for 2-dimensional local fields arising from an arithmetic surface and he formulates and proves reciprocity laws around a point and along a curve of an arithmetic surface. To have a reciprocity law along a horizontal curve, he completes horizontal curves with points at infinity, i.e. real or complex embeddings of the function field of the horizontal curve.

## 0.2 Results in this paper

At the center of our considerations there is an adelic object for an arithmetic surface  $\varphi : X \rightarrow B = \text{Spec } O_K$ . One expects that one has to take into account (archimedean) “data at infinity” of the arithmetic surface. Such an adelic space completed by data at infinity was proposed for the first time in [9]. In section 2 we present a simpler and slightly different version of it. Already at the level of local theory, adelic geometry for arithmetic surfaces is quite interesting, in fact the rings  $K_{x,y}$  can be equal characteristic or mixed characteristic 2-dimensional local fields depending whether  $y$  is horizontal or vertical. Over each point at infinity  $\sigma \in B_\infty$ , i.e. an embedding  $\sigma : K \rightarrow \mathbb{C}$  (up to conjugation), we obtain, by a base change, a curve  $X_\sigma$  over the archimedean completion  $K_\sigma$  of the number field  $K$ , that can be thought as a fibre at infinity. The completed adelic ring  $\mathbf{A}_{\widehat{X}}$  will then contain the one dimensional adelic rings relative to the fibres at infinity  $X_\sigma$ , but “counted twice”:

$$\mathbf{A}_{\widehat{X}} = \mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_{\overline{K},\sigma}} \oplus \mathbf{A}_{X_\sigma}),$$

where with  $X_{\overline{K},\sigma}$  we denote the set of closed points  $X_\sigma$  that are algebraic over  $K$ . The arithmetic counterparts  $A_{\widehat{X}}$  of the fundamental subspaces  $A_*$  are also defined. There is a specific geometric reason that suggests why we should count adeles at infinity twice, and it involves the interpretation horizontal curves on  $\widehat{X}$  in terms of Arakelov geometry i.e. we have to consider their “intersection” with fibres at infinity.

By slightly generalizing the local theory of residues for two dimensional local fields developed in [16], in section 3 we define a global adelic residue

$$\xi^\omega : \mathbf{A}_{\widehat{X}} \rightarrow \mathbb{T}$$

( $\omega$  is a fixed nonzero rational differential form and  $\mathbb{T}$  is the unit complex circle) and we show that  $\xi^\omega$  is sequentially continuous.

Section 4 is entirely dedicated to the proof of the self-duality of  $\mathbf{A}_{\widehat{X}}$  as topological additive group. In particular we show that  $\mathbf{A}_{\widehat{X}} \cong \widehat{\mathbf{A}_{\widehat{X}}}$  as topological groups and moreover that there is a character  $\psi : \mathbf{A}_{\widehat{X}} \rightarrow \mathbb{T}$  such that any other character of  $\mathbf{A}_{\widehat{X}}$  is of the form  $\psi(a \cdot)$  for  $a \in \mathbf{A}_{\widehat{X}}$ .

We define the arithmetic differential pairing

$$\begin{aligned} d_\omega : \mathbf{A}_{\widehat{X}} \times \mathbf{A}_{\widehat{X}} &\rightarrow \mathbb{T} \\ (\alpha, \beta) &\mapsto \xi^\omega(\alpha\beta). \end{aligned}$$

We improve the reciprocity laws proved in [18] by giving a set of “completed” reciprocity laws, i.e. taking into account all flags coming from points at infinity. We show that both  $A_{\widehat{01}}$  and  $A_{\widehat{02}}$  (adelic subspaces corresponding to curves and points respectively) are self-orthogonal with respect to  $d_\omega$  i.e.  $A_{\widehat{01}} = A_{\widehat{01}}^\perp$  and  $A_{\widehat{02}} = A_{\widehat{02}}^\perp$ . The inclusions  $A_{\widehat{01}} \subseteq A_{\widehat{01}}^\perp$  and  $A_{\widehat{02}} \subseteq A_{\widehat{02}}^\perp$  are a direct consequence of the completed reciprocity laws, thus the self-orthogonality of  $A_{\widehat{01}}$  and  $A_{\widehat{02}}$  can be interpreted as “strong reciprocity laws” for arithmetic surfaces. The “strong reciprocity laws” for surfaces over a perfect field were proved in [10].

The problems of finding proofs of the discreteness of the function field  $K(X)$  inside  $\mathbf{A}_{\widehat{X}}$  and of the compactness of the quotient  $\mathbf{A}_{\widehat{X}}/K(X)^\perp$  are still open, but we plan to publish a solution in a forthcoming

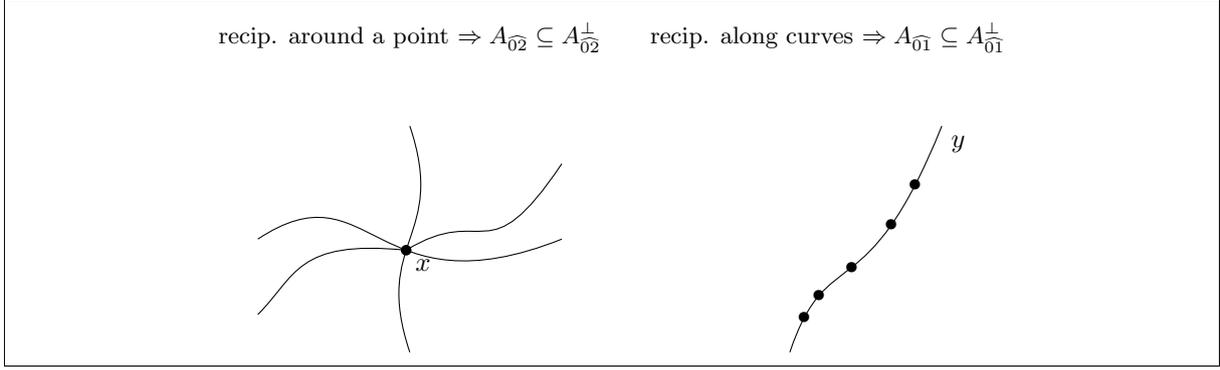


Figure 1: The sum of local two-dimensional residues is zero when a point is fixed and curves passing through it vary. The sum of local two-dimensional residues is zero when a curve is fixed and the points sitting on it vary.

paper. Finally, in analogy with the case of algebraic surfaces we show that the Arakelov intersection pairing can be lifted to the idelic group  $\mathbf{A}_X^\times$ . The schematic part of the lifting was already proved in [8], so here we solve the problem of the data carried by Green functions on fibres at infinity. It is worth remembering that Arakelov theory is the only known theory that provides consistent intersection theory on arithmetic surfaces, therefore we would expect that a theory of adèles on arithmetic surfaces should resonate with Arakelov geometry.

The text contains also two appendices which are indispensable for the understanding and moreover prerequisites for this paper are [8] and a basic knowledge of the theory of higher local fields (e.g. [17]).

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## 1 Preliminaries

### 1.1 Basic notions

**General notations** All rings are considered commutative and unitary. Let  $(A, \mathfrak{m})$  be a Noetherian local ring and let  $M$  be an  $A$ -module, then we put  $M^{\text{sep}} := M / \bigcap_{j \geq 1} \mathfrak{m}^j M$ . When we pick a point  $x$  in a scheme  $X$  we generally mean a *closed point* if not otherwise specified, also all sums  $\sum_{x \in X}$  are meant to be “over all closed points of  $X$ ”. The cardinality of a set  $T$  is denoted as  $\#(T)$ . For a number field  $K$ , with  $\bar{K}$  we denote its algebraic closure; if  $F$  is a discrete valuation field and there is no possible confusion with the previous notations, then  $\bar{F}$  is its residue field. In particular if  $a \in \mathcal{O}_F$  then  $\bar{a}$  is the image of  $a$  in  $\bar{F}$ . For a morphisms of schemes  $f : X \rightarrow S$ , the schematic preimage of  $s \in S$  is  $X_s$ . Sheaves are denoted with the “mathscr” latex  $\chi$  font; in particular the structure sheaf of a scheme  $X$  is  $\mathcal{O}_X$  (note the difference with the font  $\mathcal{O}$ ). With the symbol  $\mathbb{T}$  we denote the unit circle in the complex plane. The superscript  $\hat{\phantom{x}}$  is used several times in this paper to denote completely different objects: the dual of a topological group, the completion of a local ring or a “completed structure” in the framework of Arakelov geometry. This superposition of notation is harmless because the specific meaning of  $\hat{\phantom{x}}$  will be clear from the context.

**Topological groups** If not otherwise specified we assume that any topological group is abelian and Hausdorff. The dual of a topological group  $G$  is the group of (unitary) characters:

$$\hat{G} := \text{Hom}_{\text{cont}}(G, \mathbb{T}).$$

It is a topological group endowed with the compact-to-open topology. Moreover for a compact subset  $C \subset G$  and an open  $U \subset \mathbb{T}$  neighborhood of 1 we denote

$$\mathcal{W}(C, U) = \left\{ \chi \in \hat{G} : \chi(C) \subset U \right\} \subset \hat{G}.$$

The sets of the type  $\mathcal{W}(C, U)$  form an open base at 1 for the compact-to-open topology in  $\widehat{G}$ .

If  $G$  is algebraically and topologically isomorphic to  $\widehat{G}$ , then we say that  $G$  is *self-dual*. If  $G$  is also a ST ring (here ST means semi-topological, see appendix A for details) and  $\xi \in \widehat{G}$  is a nontrivial character, then for any  $a \in G$  the map

$$\begin{aligned} \xi_a : G &\rightarrow \mathbb{T} \\ x &\mapsto \xi(ax) \end{aligned}$$

is a character. If the map

$$\begin{aligned} \Theta_\xi : G &\rightarrow \widehat{G} \\ a &\mapsto \xi_a \end{aligned}$$

is an algebraic and topological isomorphism for any  $a \in G$ , we say that  $\xi$  is a *standard character*. For any subsets  $S \subseteq G$  and  $R \subseteq G$  we put:

$$S^\perp := \{\chi \in \widehat{G} : \chi(S) = 1\} \subseteq \widehat{G},$$

$$R^\perp := \{g \in G : \chi(g) = 1, \forall \chi \in R\} \subseteq G.$$

If  $H$  is a subgroup of  $G$ , we say that  $H$  is *dually closed* if for every element  $g \in G \setminus H$ , there is a character  $\psi \in H^\perp$  such that  $\psi(g) \neq 1$ .

We will often use the following simple general result:

**Proposition 1.1.** *Let  $G$  be a topological group such that  $G = \varinjlim_{i \in \mathbb{Z}} H_i$  where  $H_i \subset G$  is a subgroup and  $H_i \supset H_{i+1}$  for any  $i \in \mathbb{Z}$ . Then any compact subset  $C \subset G$  is contained in some  $H_i$ .*

*Proof.* Clearly  $G = \bigcup_i H_i$ . Assume that the claim is false, so we can construct a sequence of points  $\{x_i\}_{i \in \mathbb{Z}}$  in  $G$  such that  $x_i \in C \cap (H_i \setminus H_{i+1})$ . Consider now the index  $n = -i$  and put  $A = \{x_n\}_{n \geq 0}$ . If  $B \subseteq A$ , then  $B \cap H_n$  is finite for each  $n$ , so since points are closed in  $H_n$ ,  $B \cap H_n$  is closed in  $H_n$ . This means that  $B$  is closed in  $G$ . In particular,  $A$  is a closed subset of  $G$ , and every subset of  $A$  is closed so it has the discrete topology. But a closed subset of a compact space is compact, and a compact discrete space must be finite. This is a contradiction with the construction of  $A$ .  $\square$

## 1.2 Geometric setting

Let's fix the main objects and notations that we will use throughout the whole paper. Some of the material contained in this section can be found with more details in [8]. In particular we assume that the reader is familiar with the notion of 2-dimensional local field. Moreover, topological aspects of this section rely on appendix A.

Let  $K$  be a number field with ring of integers  $O_K$ . Fix the arithmetic surface  $\varphi : X \rightarrow B = \text{Spec } O_K$  which is a  $B$ -scheme with the following properties:

- $X$  is two dimensional, integral, and regular. The generic point of  $X$  is  $\eta$  and the function field of  $X$  is denoted by  $K(X)$ .
- $\varphi$  is proper and flat.
- The generic fibre, denoted by  $X_K$ , is a geometrically integral, smooth, projective curve over  $K$ . The generic point of  $B$  is denoted by  $\xi$ .

It is well known that  $\varphi$  is a projective morphism, so in particular also  $X$  is projective (see [13, Theorem 8.3.16]). Let's recall a useful result which characterizes all points of dimension 1 on  $X$ :

**Proposition 1.2.** *If  $x$  is a closed point of the curve  $X_K$ , then  $\overline{\{x\}}$  is a horizontal (prime) divisor in  $X$ . Vice versa if  $D$  is a prime divisor on  $X$ , then either  $D \subseteq X_b$  for a closed point  $b \in B$  or  $D = \overline{\{x\}}$  where  $x$  is a closed point of  $X_K$ .*

*Proof.* See for example [13, Proposition 8.3.4].  $\square$

Let  $B_\infty$  be the set of field embeddings  $\sigma : K \hookrightarrow \mathbb{C}$  up to conjugation, then  $\#B_\infty \leq [K : \mathbb{Q}]$  and the *completion* of  $B$  is the set  $\widehat{B} := B \cup B_\infty$ . For any point (i.e. nonzero prime ideal)  $b = \mathfrak{p} \in B$  we put:

- $\mathcal{O}_b := \widehat{\mathcal{O}_{B,b}}$ . It is a complete DVR.
- $K_b := \text{Frac } \mathcal{O}_b$ . It is a local field with finite residue field. The valuation is denoted by  $v_b$ .

From now on, we *always* fix a set of representatives in  $B_\infty$ . Therefore  $B_\infty$  is simply a finite set of embeddings viewed as points at infinity of  $B$ . For the non-archimedean place associated to  $b = \mathfrak{p} \in B$ , on  $K$  we choose the absolute value

$$|\cdot|_b := \mathfrak{N}(\mathfrak{p})^{-v_b(\cdot)}$$

where  $\mathfrak{N}(\mathfrak{p})$  is the cardinality of  $O_K/\mathfrak{p}$ . Moreover:

- For any real embedding  $\tau : K \rightarrow \mathbb{R}$  we consider the absolute value:

$$|\cdot|_\tau := |\tau(\cdot)|$$

where on the right hand side we mean the usual absolute value on  $\mathbb{R}$ . In this case we define the real valuation associated to  $\tau$  as

$$v_\tau(\cdot) := -\log |\cdot|_\tau$$

- For any couple of conjugate embeddings  $\sigma, \bar{\sigma} : K \rightarrow \mathbb{C}$  we choose:

$$|\cdot|_\sigma := |\sigma(\cdot)|$$

where on the right hand side we have the usual absolute value on  $\mathbb{C}$ <sup>1</sup>. Note that  $|\cdot|_\sigma$  doesn't depend on the choice between  $\sigma$  and  $\bar{\sigma}$ , since they give the same absolute value. The associated real valuation is

$$v_\sigma(\cdot) := -\log |\cdot|_\sigma.$$

For  $\sigma \in B_\infty$ ,  $K_\sigma$  is the completion of  $K$  with respect to  $|\cdot|_\sigma$ , thus  $K_\sigma = \mathbb{C}$  or  $K_\sigma = \mathbb{R}$ . Furthermore, let's introduce a constant, associated to each  $\sigma \in B_\infty$ :

$$\epsilon_\sigma := \begin{cases} 1 & \text{if } \sigma \text{ is real} \\ 2 & \text{if } \sigma \text{ is complex.} \end{cases}$$

The adelic ring of  $\widehat{B}$  (or equivalently of the number field  $K$ ) is denoted by  $\mathbf{A}_{\widehat{B}}$  or more classically also by  $\mathbf{A}_K$ , whereas  $\mathbf{A}_B := \mathbf{A}_{\widehat{B}} \cap \prod_{b \in B} K_b$  is the ring of finite adeles. Another notation for the ring of finite adeles is  $\mathbf{A}_K^f$ . For any  $\sigma \in B_\infty$  consider the base change diagram:

$$\begin{array}{ccc} X_\sigma := X \times_B \text{Spec } K_\sigma & \longrightarrow & \text{Spec } K_\sigma \\ \downarrow \varphi_\sigma & & \downarrow \text{Spec } \sigma \\ X & \xrightarrow{\varphi} & B. \end{array} \quad (1)$$

By the properties of the fibred product, it turns out that  $X_\sigma \rightarrow \text{Spec } K_\sigma$  is an integral (integrality is a consequence of the geometrical integrality of  $X_K$ ), regular projective curve over  $\mathbb{C}$  or  $\mathbb{R}$ . We denote the function field of  $X_\sigma$  by the symbol  $K_\sigma(X_\sigma)$ .

*Remark 1.3.* Diagram (1) arises from the following rather obvious commutative diagram:

$$\begin{array}{ccc} X_\sigma & \longrightarrow & \text{Spec } K_\sigma \\ \downarrow \beta_\sigma & & \downarrow \text{Spec } \sigma \\ \varphi_\sigma \left( \begin{array}{ccc} X_K & \longrightarrow & \text{Spec } K \\ \downarrow & & \downarrow \text{Spec } \iota \\ X & \longrightarrow & B \end{array} \right. & & \end{array}$$

where  $\iota : O_K \hookrightarrow K$  is the natural embedding and the map  $\beta_\sigma$  is surjective. In other words  $\varphi_\sigma$  maps surjectively  $X_\sigma$  onto the curve  $X_K$ . Since the morphisms  $\iota$  and  $\sigma$  are both flat and flatness is preserved after base change, we can conclude that  $\varphi_\sigma$  is flat. The map  $\beta_\sigma : X_\sigma \rightarrow X_K$  deserves particular attention. We denote with  $X_{\overline{K},\sigma}$  the set of closed points of  $p \in X_\sigma$  such that  $\beta_\sigma(p)$  is a closed point of  $X_K$  and we will say that  $X_{\overline{K},\sigma}$  is the set of *algebraic points* of  $X_\sigma$ . Whereas a closed point of  $X_\sigma$  which is not algebraic is said *transcendental*. The closed points of  $X_K$  have a finite number of preimages through  $\beta_\sigma$ .

<sup>1</sup>Many authors in this case take the square of the complex absolute value to keep track of the fact that point at infinity induced by  $|\cdot|_\sigma$  is “complex”, so roughly speaking “of order two”. We will fix this by using the coefficient 2 when necessary.

With the notation  $\widehat{X}$ , we define the “completed surface”

$$\widehat{X} := X \cup \bigcup_{\sigma \in B_\sigma} X_\sigma.$$

A curve  $Y$  on  $X$  will always be an integral curve and its unique generic point will be denoted with the letter  $y$ . For simplicity we will often identify  $Y$  with its generic point  $y$ , which means that by an abuse of language and notation we will use sentences like “let  $y \subset X$  be a curve on  $X$ ...”. A *flag* on  $X$  is a couple  $(x, y)$  where  $x$  is a closed point sitting on a curve  $y \subset X$ , it will be denoted simply as  $x \in y$ .

**Definition 1.4.** Fix a closed point  $x \in X$ , then:

- $\mathcal{O}_x := \widehat{\mathcal{O}_{X,x}}$ . It is a Noetherian, complete, regular, local, domain of dimension 2 with maximal ideal  $\widehat{\mathfrak{m}}_x$ .
- $K'_x := \text{Frac } \mathcal{O}_x$ .
- $K_x := K(X)\mathcal{O}_x \subseteq K'_x$ .

For a curve  $y \subset X$  we put:

- $\mathcal{O}_y := \widehat{\mathcal{O}_{X,y}}$ . It is a complete DVR with maximal ideal  $\widehat{\mathfrak{m}}_y$ .
- $K_y := \text{Frac } \mathcal{O}_y$ . It is a complete discrete valuation field with valuation ring  $\mathcal{O}_y$ . The valuation is denoted by  $v_y$ .

For a flag  $x \in y \subset X$ , we have a surjective local homomorphism  $\mathcal{O}_{X,x} \rightarrow \mathcal{O}_{y,x}$ , with kernel  $\mathfrak{p}_{y,x}$ , induced by the closed embedding  $y \subset X$  (note that  $\mathfrak{p}_{y,x}$  is a prime ideal of height 1). The inclusion  $\mathcal{O}_{X,x} \subset \mathcal{O}_x$  induces a morphism of schemes  $\varphi: \text{Spec } \mathcal{O}_x \rightarrow \text{Spec } \mathcal{O}_{X,x}$  and we define the *local branches of  $y$  at  $x$*  as the elements of the set

$$y(x) := \varphi^{-1}(\mathfrak{p}_{y,x}) = \{ \mathfrak{z} \in \text{Spec } \mathcal{O}_x : \mathfrak{z} \cap \mathcal{O}_{X,x} = \mathfrak{p}_{y,x} \}.$$

If  $y(x)$  contains only an element, we say that  $y$  is unbranched at  $x$ . Fix a flag  $x \in y \subset X$  with  $\mathfrak{z} \in y(x)$ , then we have the 2-dimensional local field

$$K_{x,\mathfrak{z}} := \text{Frac} \left( \widehat{(\mathcal{O}_x)_{\mathfrak{z}}} \right)$$

explicitly obtained in the following way: we localise  $\mathcal{O}_x$  at the prime ideal  $\mathfrak{z}$ , complete it at its maximal ideal and finally we take the fraction field. The ring of integers of  $K_{x,\mathfrak{z}}$  is denoted by  $\mathcal{O}_{x,\mathfrak{z}} := \mathcal{O}_{K_{x,\mathfrak{z}}} = \widehat{(\mathcal{O}_x)_{\mathfrak{z}}}$ . All the needed material about higher local fields is contained in [8, 1.1], whereas for a deeper study the reader can consult [11]; see also a more recent introduction in [17].

**Definition 1.5.** Let  $x \in y \subset X$  be a flag and let  $\mathfrak{z} \in y(x)$ , then the first residue field of  $K_{x,\mathfrak{z}}$  is  $E_{x,\mathfrak{z}} := K_{x,\mathfrak{z}}^{(1)}$  and the second residue field is  $k_{\mathfrak{z}}(x) := K_{x,\mathfrak{z}}^{(2)}$ . The valuation on  $K_{x,\mathfrak{z}}$  is  $v_{x,\mathfrak{z}}$  and the valuation on  $E_{x,\mathfrak{z}}$  is  $v_{x,\mathfrak{z}}^{(1)}$ ; whereas  $\mathcal{O}_{K_{x,\mathfrak{z}}}^{(2)} := \{ a \in \mathcal{O}_{x,\mathfrak{z}} : \bar{a} \in \mathcal{O}_{E_{x,\mathfrak{z}}} \}$ .

$$\begin{array}{ccccc}
 K_{x,\mathfrak{z}} & \supset & \mathcal{O}_{x,\mathfrak{z}} := \mathcal{O}_{K_{x,\mathfrak{z}}} & \supset & \mathcal{O}_{K_{x,\mathfrak{z}}}^{(2)} \\
 & & \downarrow & & \downarrow \\
 & & E_{x,\mathfrak{z}} := K_{x,\mathfrak{z}}^{(1)} & \supset & \mathcal{O}_{E_{x,\mathfrak{z}}} \\
 & & & & \downarrow \\
 & & & & k_{\mathfrak{z}}(x) := K_{x,\mathfrak{z}}^{(2)}
 \end{array}$$

(Dashed arrows indicate inclusions:  $K_{x,\mathfrak{z}} \supset E_{x,\mathfrak{z}}$  and  $E_{x,\mathfrak{z}} \supset k_{\mathfrak{z}}(x)$ )

Moreover we put:

$$\begin{aligned}
 K_{x,y} &:= \prod_{\mathfrak{z} \in y(x)} K_{x,\mathfrak{z}}, & \mathcal{O}_{x,y} &:= \prod_{\mathfrak{z} \in y(x)} \mathcal{O}_{x,\mathfrak{z}}, \\
 E_{x,y} &:= \prod_{\mathfrak{z} \in y(x)} E_{x,\mathfrak{z}}, & k_y(x) &:= \prod_{\mathfrak{z} \in y(x)} k_{\mathfrak{z}}(x).
 \end{aligned}$$

Let's endow  $\mathcal{O}_{X,x}$  with the  $\mathfrak{m}_x$ -adic topology with respect to its maximal ideal, then  $K_{x,\mathfrak{z}}$  can be endowed with a canonical topology by using the following steps explained in appendix A.2:

$$\mathcal{O}_{X,x} \xrightarrow{(C)} \mathcal{O}_x = \widehat{\mathcal{O}_{X,x}} \xrightarrow{(L)} (\mathcal{O}_x)_{\mathfrak{z}} \xrightarrow{(C)} \widehat{(\mathcal{O}_x)_{\mathfrak{z}}} \xrightarrow{(L)} K_{x,\mathfrak{z}} = \text{Frac} \left( \widehat{(\mathcal{O}_x)_{\mathfrak{z}}} \right). \quad (2)$$

Then  $K_{x,y}$  is endowed with the product topology and it is a ST ring (see appendix A for an introduction to semi-topological structures). Here it is very important to point out that  $K_{x,y}$  is not a topological ring, since it turns out that the multiplication is not continuous as function of two variables.

*Remark 1.6.* This is one of the several ways to topologise  $K_{x,y}$ ; see for example [5, 1.] for a survey. It is not the most explicit topology for  $K_{x,y}$ , but it is independent from the choice of the uniformizing parameter since it is obtained by a general process of localizations and completions.

If  $y$  is a horizontal curve then  $K_{x,\mathfrak{z}}$  is of equal characteristic and isomorphic to  $E_{x,\mathfrak{z}}((t))$  where  $E_{x,\mathfrak{z}}$  is a finite extension of  $\mathbb{Q}_p$  and  $t$  is (the image of) a uniformizing parameter. If  $y$  is a vertical curve then  $K_{x,\mathfrak{z}}$  is of mixed characteristic and isomorphic to a finite extension of  $K_p\{\{t\}\}$  where  $K_p$  is a finite extension of  $\mathbb{Q}_p$  (see [8, example 1.7] for the definition of  $K_p\{\{t\}\}$ ). In this case  $t$  it is not (the image of) a uniformizing parameter, but it is (the image of) a uniformizing parameter for  $E_{x,\mathfrak{z}} \cong \overline{K}_p((t))$ . It is always possible to choose a uniformizing parameter  $t_y$  of  $K_y$  to be also the uniformizing parameter of  $K_{x,\mathfrak{z}}$  for all  $x \in y$ , this will be our canonical choice if not otherwise specified.

If  $\varphi(x) = b$  we have an embedding  $K_b \hookrightarrow K_{x,\mathfrak{z}}$ , and we say that  $K_{x,\mathfrak{z}}$  is an arithmetic 2-dimensional local field over  $K_b$ . The module of differential forms relative to  $x$  and  $\mathfrak{z} \in y(x)$  is the  $K_{x,\mathfrak{z}}$ -vector space:

$$\Omega_{x,\mathfrak{z}}^1 := \left( \Omega_{\mathcal{O}_{x,\mathfrak{z}}|\mathcal{O}_b}^1 \right)^{\text{sep}} \otimes_{\mathcal{O}_{x,\mathfrak{z}}} K_{x,\mathfrak{z}},$$

where  $\Omega_{\mathcal{O}_{x,\mathfrak{z}}|\mathcal{O}_b}^1$  is the usual module of Kähler differential forms and the operator “sep” was defined at the end of section 1.1 in the “General notations” paragraph. Then,  $\Omega_{x,\mathfrak{z}}^1$  is endowed with a natural topology inherited from  $K_{x,\mathfrak{z}}$ . In [16] and [18] it is defined the residue map:

$$\text{res}_{x,\mathfrak{z}} : \Omega_{x,\mathfrak{z}}^1 \rightarrow K_b$$

with the following properties:

- It is  $K_b$ -linear.
- It is continuous (this is shown in [18, Lemma 2.8, Remark 2.9]).

A more detailed description of  $\Omega_{x,\mathfrak{z}}^1$  and  $\text{res}_{x,\mathfrak{z}}$  will be given in section 3.

The global adelic theory for the projective scheme  $X$  is described in [8, 1.2]. We obtain the adelic ring  $\mathbf{A}_X$  as a “double restricted product” of the rings  $K_{x,y}$  performed first over closed points ranging on curves, and then over all curves in  $X$ . Fix any curve  $y \subset X$  and denote by  $\mathfrak{J}_{x,y}$  the Jacobson radical of  $\mathcal{O}_{x,y}$ ; we put

$$\mathbb{A}_y^{(0)} := \left\{ (\alpha_{x,y})_{x \in y} \in \prod_{x \in y} \mathcal{O}_{x,y} : \forall s > 0, \alpha_{x,y} \in \mathcal{O}_x + \mathfrak{J}_{x,y}^s \right\} \subset \prod_{x \in y} \mathcal{O}_{x,y}.$$

Then for any  $r \in \mathbb{Z}$  and for any choice of uniformizing parameter  $t_y$

$$\mathbb{A}_y^{(r)} := \widehat{\mathfrak{m}}_y^r \mathbb{A}_y^{(0)} = t_y^r \mathbb{A}_y^{(0)} \subset \prod_{x \in y} K_{x,y}.$$

Clearly  $\mathbb{A}_y^{(r)} \supseteq \mathbb{A}_y^{(r+1)}$  and  $\bigcap_{r \in \mathbb{Z}} \mathbb{A}_y^{(r)} = 0$ ; moreover we define

$$\mathbb{A}_y := \bigcup_{r \in \mathbb{Z}} \mathbb{A}_y^{(r)}.$$

**Definition 1.7.** The ring of adèles of  $X$  is

$$\mathbf{A}_X := \left\{ (\beta_y)_{y \subset X} \in \prod_{y \subset X} \mathbb{A}_y : \beta_y \in \mathbb{A}_y^{(0)} \text{ for all but finitely many } y \right\} \subset \prod_{\substack{x \in y, \\ y \subset X}} K_{x,y},$$

Finally we recall the definitions of some important subspaces of  $\mathbf{A}_X$ . Consider the following diagonal embeddings:

$$K_x \subset \prod_{y \ni x} K_{x,y}, \quad K_y \subset \prod_{x \in y} K_{x,y},$$

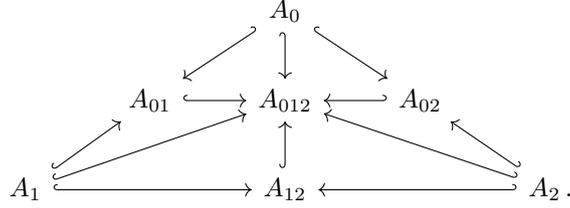
so we can put:

$$\prod_{x \in X} K_x \subset \prod_{\substack{x \in y \\ y \subset X}} K_{x,y}, \quad \prod_{y \subset X} K_y \subset \prod_{\substack{x \in y \\ y \subset X}} K_{x,y}.$$

then we define

$$\begin{aligned} A_{012} &:= \mathbf{A}_X; & A_{12} &:= \mathbf{A}_X \cap \prod_{\substack{x \in y \\ y \subset X}} \mathcal{O}_{x,y} = \prod_{y \subset X} \mathbb{A}_y^{(0)}; \\ A_{02} &:= \mathbf{A}_X \cap \prod_{x \in X} K_x; & A_2 &:= \mathbf{A}_X \cap \prod_{x \in X} \mathcal{O}_x; & A_{01} &:= \mathbf{A}_X \cap \prod_{y \subset X} K_y; \\ A_1 &:= \mathbf{A}_X \cap \prod_{y \subset X} \mathcal{O}_y; & A_0 &:= K(X). \end{aligned}$$

The subspaces satisfy a series of inclusion relations depicted in the following diagram:



If  $D = \sum_{y \subset X} n_y [y]$  is a divisor of  $X$  we can define the subgroups

$$\mathbf{A}_X(D) := \prod_{y \subset X} \mathbb{A}_y^{(-n_y)}.$$

Note that  $\mathbf{A}_X(D)$  is a well defined subgroup of  $\mathbf{A}_X$  because  $n_y = 0$  for all but finitely many  $y$ . Let's define the subspaces

$$\begin{aligned} A_{12}(D) &:= A_{012} \cap \mathbf{A}_X(D) = \mathbf{A}_X(D). \\ A_1(D) &:= A_{01} \cap \mathbf{A}_X(D); & A_2(D) &:= A_{02} \cap \mathbf{A}_X(D); \end{aligned}$$

When  $X$  is an algebraic surface over a perfect field  $k$ , the algebraic and topological properties of the subspaces  $A_*$  were studied in [10].

### 1.3 Topology on adelic structures.

In this crucial subsection we explain how to put a topology on all adelic structures introduced so far. We point out that all categorical limit considered here are in the category linear topological groups (so linear direct/inverse limits). For more details see appendix A.

- For any  $s > 0$  let's put:

$$\mathbb{A}_y^{(0)}\{s\} := \{(a_{x,y})_{x \in y} \in \prod_{x \in y} \mathcal{O}_{x,y} : a_{x,y} \in \mathcal{O}_x + \mathfrak{J}_{x,y}^s \text{ for all but fin. many } x \in y\}.$$

Endow  $\mathbb{A}_y^{(0)}\{s\}$  with the restricted product topology i.e. linear direct limit.

- $\mathbb{A}_y^{(0)} = \bigcap_{s \geq 0} \mathbb{A}_y^{(0)}\{s\}$ , so we put on  $\mathbb{A}_y^{(0)}$  the linear inverse limit topology.
- The topology is transferred from  $\mathbb{A}_y^{(0)}$  to  $\mathbb{A}_y^{(r)}$  for any  $r \in \mathbb{Z}$ , by the multiplication by  $t_y^r$ .
- Each  $\mathbb{A}_y^{(r)} / \mathbb{A}_y^{(r+j)}$ , for  $j > 0$ , is endowed with the quotient topology.

- We endow  $\mathbb{A}_y = \varinjlim \mathbb{A}_y^{(r)} = \bigcup_r \mathbb{A}_y^{(r)}$  with the linear direct limit topology.
- $\mathbf{A}_X$  is the restricted product i.e. linear direct limit of the topological groups  $\mathbb{A}_y$  with respect to  $\mathbb{A}_y^{(0)}$ .

Since  $\mathcal{O}_x + \mathfrak{J}_{x,y}$  surjects onto  $E_{x,y}$ , it is easy to see that the natural projection (which is continuous and open)

$$\begin{aligned} p_y : \mathbb{A}_y^{(0)} &\rightarrow \mathbf{A}_{k(y)}^f \\ (a_{x,y})_{x \in y} &\mapsto (\overline{a_{x,y}})_{x \in y} \end{aligned}$$

induces an algebraic and topologic isomorphism between  $\mathbb{A}_y^{(0)}/\mathbb{A}_y^{(1)}$  and the ring of the one dimensional finite adeles  $\mathbf{A}_{k(y)}^f$ . Consider the exact sequence:

$$0 \rightarrow \mathbb{A}_y^{(1)}/\mathbb{A}_y^{(2)} \rightarrow \mathbb{A}_y^{(0)}/\mathbb{A}_y^{(2)} \rightarrow \mathbb{A}_y^{(0)}/\mathbb{A}_y^{(1)} \rightarrow 0$$

Since  $\mathbb{A}_y^{(1)}/\mathbb{A}_y^{(2)}$  and  $\mathbb{A}_y^{(0)}/\mathbb{A}_y^{(1)}$  are locally compact and self-dual, then  $\mathbb{A}_y^{(0)}/\mathbb{A}_y^{(2)}$  is locally compact. We conclude that for any  $j > 0$  the quotient  $\mathbb{A}_y^{(r)}/\mathbb{A}_y^{(r+j)}$  is a locally compact topological group (hence complete).

**Proposition 1.8.** *The following two fundamental topological properties hold:*

- (i)  $\mathbb{A}_y^{(r)}$  is complete for any  $r \in \mathbb{Z}$  (but in general is not locally compact).
- (ii) For each open neighborhood  $U \subset \mathbb{A}_y^{(r)}$  of 0 there is  $s > r$  such that  $\mathbb{A}_y^{(s)} \subset U$ .

*Proof.* (i) is true since  $\mathcal{O}_{x,y}$  is complete and  $\mathcal{O}_x + \mathfrak{J}_{x,y}^s$  is closed in  $\mathcal{O}_{x,y}$ . (ii) can be checked directly from the above definition of the topology.  $\square$

**Proposition 1.9.** *There is an algebraic and topological isomorphism*

$$\mathbb{A}_y^{(r)} \cong \varprojlim_{j>0} \mathbb{A}_y^{(r)}/\mathbb{A}_y^{(r+j)}$$

*Proof.* Thanks to Proposition 1.8, we can apply directly [4, III §7.3, Corollary 1].  $\square$

In particular  $\mathbb{A}_y^{(r)} \cong t_y^r \mathbb{A}_y^{(0)}[[t_y]]$ . The open subgroups of  $\mathbb{A}_y$  that form a local basis at 0 can be described in the following way: fix a sequence  $\{U_i\}_{i \in \mathbb{Z}}$  of open sets in  $\mathbb{A}_y^{(0)}$  with the property that there exists  $k \in \mathbb{Z}$  such that  $U_i = \mathbb{A}_y^{(0)}$  for  $i \geq k$ . Then we consider the open set

$$\sum' U_i t_y^i := \left\{ \text{Laurent series } \sum a_j t_y^j \text{ such that } a_j \in U_j \right\}.$$

Each open neighborhood  $U \subset \mathbb{A}_y$  of 0 contains some  $\mathbb{A}_y^{(r)}$ .

## 2 The ring of completed adeles $\mathbf{A}_{\widehat{X}}$ and its subspaces

We want to define adeles for arithmetic surfaces in a way that preserves the most fundamental properties of the adelic theory and is compatible with Arakelov geometry. In particular, we have to consider points at infinity of the base and, corresponding to them, infinite fibres. When we add a fibre at infinity  $X_\sigma$  to the picture, we have to take in account *all* possible flags on the completed surface  $\widehat{X}$ : an algebraic closed point  $p$  on a fibre at infinity  $X_\sigma$  originates a flag  $p \in X_\sigma$ , but it can be seen also as an ‘‘intersection point’’ between a completed horizontal curve  $\bar{y}$  and  $X_\sigma$ . On the other hand  $X_\sigma$  is the only curve containing a transcendental point  $p \in X_\sigma$ .

Let  $y$  be a curve on  $X$ , if  $y$  is vertical then we put  $\bar{y} = y$ , if  $y$  is horizontal, then by  $\bar{y}$  we mean:

$$\bar{y} = y \cup \bigcup_{\sigma \in B_\infty} y_\sigma$$

where

$$y_\sigma = \varphi_\sigma^*(y) \in \text{Div}(X_\sigma).$$

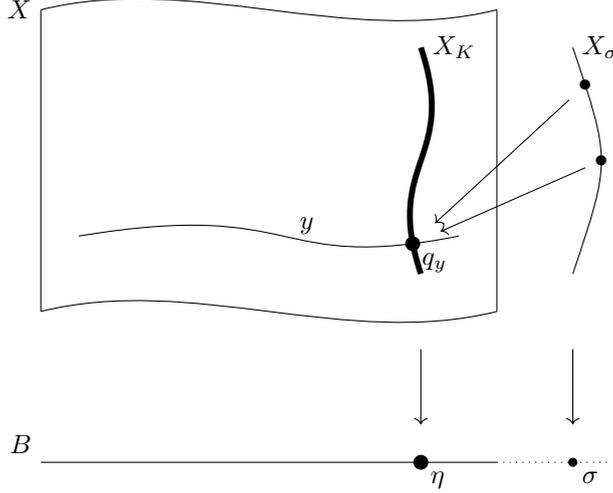


Figure 2: A visual example where  $y_\sigma$  is made of two points (marked on the curve  $X_\sigma$ ). The generic point of the curve  $y$  here is denoted by  $q_y$ .

By simplicity we also put  $y_\infty := \cup_{\sigma \in B_\infty} y_\sigma$ , so we have the decomposition  $\bar{y} = y \cup y_\infty$ . Any point  $p \in X_{\bar{K},\sigma} \subset X_\sigma$  lies on a completed horizontal curve  $\bar{y}$  because we have the map  $X_\sigma \rightarrow X_K \subset X$  and closed points of the generic fibre  $X_K$  are in bijective correspondence with horizontal curves of  $X$ . From now on, a curve on  $\hat{X}$  will be always a completed curve  $\bar{y}$ , and a point  $x \in \bar{y}$  can be also a point lying on some “part at infinity”  $y_\sigma$  (when  $y$  is horizontal), if not explicitly said otherwise.

The local data of the completed adelic ring will be the following ones:

- For any flag at infinity  $p \in X_\sigma$  we put

$$K_{p,\sigma} := \text{Frac} \left( \widehat{\mathcal{O}_{X_\sigma,p}} \right).$$

In other words  $K_{p,\sigma}$  is a local field isomorphic to  $K_\sigma((t))$ . The valuation ring of  $K_{p,\sigma}$  is  $\mathcal{O}_{p,\sigma} \cong K_\sigma[[t]]$  and  $E_{p,\sigma} \cong K_\sigma$  is the residue field.

- If  $p \in \bar{y}$  and  $p \in y_\sigma$  for some  $\sigma \in B_\infty$ , we put

$$K_{p,\bar{y}} := K_{p,\sigma}, \quad \mathcal{O}_{p,\bar{y}} := \mathcal{O}_{p,\sigma}, \quad E_{p,\bar{y}} := E_{p,\sigma};$$

- For any other point  $x \in y$  we have:

$$K_{x,\bar{y}} := K_{x,y}, \quad \mathcal{O}_{x,\bar{y}} := \mathcal{O}_{x,y}, \quad E_{x,\bar{y}} := E_{x,y}, \quad k_{\bar{y}}(x) = k_y(x).$$

When  $p$  is a point at infinity we want to consider the fields  $K_{p,\sigma}$  and  $K_{p,\bar{y}}$  as 2-dimensional local fields, but if we use a completion/localization topology as described in equation (2), we obtain the usual one dimensional valuation topology. Therefore we fix some isomorphisms  $K_{p,\sigma} \cong K_{p,\bar{y}} \cong K_\sigma((t))$  (parametrizations), we consider  $K_\sigma$  with the standard topology given by its archimedean norm, and we endow  $K_\sigma((t))$  with the ind/pro-topology (see appendix A.2). Then we carry such a topology on  $K_{p,\sigma}$  and  $K_{p,\bar{y}}$  through the parametrizations. The ind/pro-topology on  $K_\sigma((t))$  is coarser than the 1-dimensional valuation topology. Let’s emphasize the fact that in order to define a topology on the 2-dimension local fields at infinity we need to fix an isomorphism with  $K_\sigma((t))$ , so from now on we assume that such a choice has been made.

*Remark 2.1.* In the product  $\prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \hat{X}}} K_{x,\bar{y}}$  we find three different types of 2-dimensional local fields:  $K_p((t))$ , finite extensions of  $K_p\{\{t\}\}$  and  $K_\sigma((t))$ .

We are going to define a new ring  $\bar{\mathbf{A}}_X$  which will be a subspace of the big product  $\prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \hat{X}}} K_{x,\bar{y}}$ . Let’s first extend the spaces  $\mathbb{A}_y^{(r)}$  for completed curves:

**Definition 2.2.** For any completed curve  $\bar{y}$  let's put:

$$\begin{aligned}\mathbb{A}_{\bar{y}} &:= \mathbb{A}_y \oplus \prod_{p \in y_\infty} K_{p, \bar{y}}, \\ \mathbb{A}_{\bar{y}}^{(0)} &:= \mathbb{A}_y^{(0)} \oplus \prod_{p \in y_\infty} \mathcal{O}_{p, \bar{y}}, \\ \mathbb{A}_{\bar{y}}^{(r)} &:= \mathbb{A}_y^{(r)} \oplus \prod_{p \in y_\infty} \mathfrak{p}_{K_{p, \bar{y}}}^r \mathcal{O}_{p, \bar{y}},\end{aligned}$$

and endow them with the finite product topology.

Again each  $\mathbb{A}_{\bar{y}}^{(r)}$  is closed in  $\mathbb{A}_{\bar{y}}$  and the latter can be thought as a first restricted product performed on the completed curve  $\bar{y}$ . We can use the formal notation:

$$\mathbb{A}_{\bar{y}} = \prod'_{x \in \bar{y}} K_{x, \bar{y}}.$$

Let's assume by simplicity that  $y$  is a regular horizontal curve, then  $K_{x, y} \cong E_{x, y}((t))$  where  $E_{x, y}$  is a finite extension of  $\mathbb{Q}_p$  and it is the completion of the field  $k(y)$  with respect to the valuation induced by the inclusion  $x \in y$ . Moreover  $y = \text{Spec } \mathcal{O}_L$  where  $L$  is a finite extension of  $K$ . In general if  $y$  is any horizontal curve admitting singular points, then  $y = \text{Spec } R$  where  $R$  is an order of  $L$ . For any curve  $y$  we have

$$\mathbf{A}_{k(y)} = \prod'_{x \in y} k(y)_x \oplus \prod_{q \in y_\infty} K_q,$$

where the restricted product is with respect to the complete discrete valuation rings corresponding to the points  $x \in y$ . In other words we recover the classical 1-dimensional adelic ring of attached to the number field  $k(y) = L$ .

**Lemma 2.3.** *Let  $y$  be a regular horizontal curve and let  $t$  be a uniformizing parameter of  $K_y$ . For any  $r \in \mathbb{Z}$ ,  $\mathbb{A}_y^{(r)}$  is equal to the following ring:*

$$\Xi_y^{(r)} := \left\{ (\alpha_{x, y})_{x \in y} \in \prod_{x \in y} K_{x, y} : \alpha_{x, y} \text{ satisfies the following conditions } (*) \text{ and } (**) \right\}$$

$$(*) \quad \alpha_{x, y} \in t^r E_{x, y}[[t]].$$

(\*\*) *Assume that:*

$$\alpha_{x, y} = t^r \sum_{i \geq 0} \Gamma_{x, i} t^i \quad \text{with } \Gamma_{x, i} \in E_{x, y},$$

*then for any fixed index  $i$  the sequence  $(\Gamma_{x, i})_{x \in y} \in \mathbf{A}_{k(y)}^f$ . In other words for all but finitely many  $x \in y$  we have that  $\Gamma_{x, i} \in \mathcal{O}_{E_{x, y}}$ .*

*Proof.* Inclusion  $\mathbb{A}_y^{(r)} \subseteq \Xi_y^{(r)}$ . Let's start with  $r = 0$ , the general case will follow trivially. Consider an element  $(\alpha_{x, y})_{x \in y}$ , then clearly (\*) is true because  $\mathcal{O}_{x, y} = E_{x, y}[[t]]$ . Suppose that  $\alpha_{x, y} = \sum_{i \geq 0} \Gamma_{x, i} t^i$ , then there exists a decomposition:

$$\alpha_{x, y} = \sum_{i \geq 0} \Theta_{x, i} t^i + \sum_{i \geq 0} \Lambda_{x, i} t^i \in \mathcal{O}_x + \mathcal{O}_{x, y}$$

where  $\Theta_{x, i} \in \mathcal{O}_{E_{x, y}}$ ,  $\Lambda_{x, i} \in E_{x, y} \setminus \mathcal{O}_{E_{x, y}}$ , and  $\Gamma_{x, i} = \Theta_{x, i} + \Lambda_{x, i}$ . Now fix an index  $h \geq 0$ , then the set

$$S_h := \{x \in y : \Lambda_{x, h} \neq 0\}$$

is finite, indeed note that  $\mathcal{O}_x + \mathfrak{J}_{x, y}^s = \mathcal{O}_{E_{x, y}}[[t]] + t^s E_{x, y}[[t]]$ , thus if  $\Lambda_{x, h} \neq 0$ , then  $\alpha_{x, y} \notin \mathcal{O}_x + \mathfrak{J}_{x, y}^{h+1}$ . In other words if for infinitely many  $x \in y$  we had that  $\Lambda_{x, h} \neq 0$ , then for the same points  $\alpha_{x, y} \notin \mathcal{O}_x + \mathfrak{J}_{x, y}^{h+1}$  against the definition of  $\mathbb{A}_y^{(0)}$ . We have shown that for all but finitely many  $x \in y$ ,  $\Gamma_{x, i} = \Theta_{x, i} \in \mathcal{O}_{E_{x, y}}$  which is equivalent to say that  $(\Gamma_{x, i})_{x \in y} \in \mathbf{A}_{k(y)}^f$ .

The case when  $r \neq 0$  follows easily from the fact that  $\widehat{\mathfrak{m}}_y^r \Xi_y^{(0)} = \Xi_y^{(r)}$ .

Inclusion  $\Xi_y^{(r)} \subseteq \mathbb{A}_y^{(r)}$ . As above it is enough to write the proof for  $r = 0$ . Let  $(\alpha_{x,y})_{x \in y} \in \Xi_y^{(0)}$ , then for any index  $i \geq 0$  define:

$$T_i := \{x \in y : \Gamma_{x,i} \notin \mathcal{O}_{E_{x,y}}[[t]]\};$$

by the property (\*\*)  $T_i$  is a finite set. Now fix an index  $h > 0$  then for all  $x \in y \setminus \bigcup_{i=1}^{h-1} T_i$ , (i.e. for all but finitely many  $x \in y$ ) it holds that  $\Gamma_{x,i} = \Theta_{x,i}$  when  $i < h$ , which means that

$$\alpha_{x,y} = \sum_{i \geq 0} \Theta_{x,i} t^i + \sum_{i \geq h} \Lambda_{x,i} t^i \in \mathcal{O}_x + \mathfrak{J}_{x,y}^h.$$

□

**Proposition 2.4.** *Let  $y$  be a regular horizontal curve and let  $t$  be a uniformizing parameter of  $K_y$ . For any  $r \in \mathbb{Z}$ ,  $\mathbb{A}_y^{(r)} \cong t^r \mathbf{A}_{k(y)}[[t]]$ . In particular  $\mathbb{A}_{\bar{y}} \cong \mathbf{A}_{k(y)}((t))$  and  $\mathbb{A}_{\bar{y}}^{(0)} \cong \mathbf{A}_{k(y)}[[t]]$ .*

*Proof.* By Lemma 2.3 we have the equality  $\mathbb{A}_y^{(r)} = \Xi_y^{(r)}$  and the map  $\Xi_y^r \rightarrow t^r \mathbf{A}_{k(y)}^f[[t]]$  is given in the following way and it is well defined:

$$(\alpha_{x,y})_{x \in y} = \left( t_2^r \sum_{i \geq 0} \Gamma_{x,i} t_2^i \right)_{x \in y} \mapsto t^r \sum_{i \geq 0} (\Gamma_{x,i})_{x \in y} t^i.$$

It is routine check to show that is a ring isomorphism. □

*Remark 2.5.* Proposition 2.4 is true also when  $y$  is a singular curve. The proof is based on a slightly modified version of Lemma 2.3; the only difference consists in the fact that if  $x \in y$  is singular then  $K_{x,y} = \prod_{\mathfrak{z} \in y(x)} K_{x,\mathfrak{z}}$  is a sum of 2-dimensional valuation fields and  $\mathfrak{J}_{x,y}$  is the sum of the maximal ideals of  $K_{x,\mathfrak{z}}$ . Here we restricted the proof to the case of non-singular curves just by simplicity of notations.

**Definition 2.6.** The modified version of  $\mathbf{A}_X$  which takes in account the completed curves is:

$$\overline{\mathbf{A}}_X := \left\{ (\beta_{\bar{y}})_{\bar{y} \subset \widehat{X}} \in \prod_{\bar{y} \subset \widehat{X}} \mathbb{A}_{\bar{y}} : \beta_{\bar{y}} \in \mathbb{A}_{\bar{y}}^{(0)} \text{ for all but finitely many } \bar{y} \right\} \subset \prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \widehat{X}}} K_{x,\bar{y}}.$$

We also introduce the formal notation

$$\overline{\mathbf{A}}_X = \prod''_{\substack{x \in \bar{y}, \\ \bar{y} \subset \widehat{X}}} K_{x,\bar{y}}.$$

The topology on  $\overline{\mathbf{A}}_X$  is the restricted topology of the additive groups  $\mathbb{A}_{\bar{y}}$  with respect to  $\mathbb{A}_{\bar{y}}^{(0)}$ .

**Definition 2.7.** The *completed adelic ring* attached to  $\widehat{X}$  is

$$\mathbf{A}_{\widehat{X}} := \overline{\mathbf{A}}_X \oplus \prod_{\sigma \in B_\infty} \mathbf{A}_{X_\sigma}$$

where each  $\mathbf{A}_{X_\sigma}$  is the adelic ring of the curve  $X_\sigma$ . The topology on  $\mathbf{A}_{\widehat{X}}$  is the product topology.

Let  $\Upsilon$  be the collection of all finite sets of completed curves of  $\widehat{X}$ , then for  $S \in \Upsilon$  we define

$$\mathbf{A}_{\widehat{X}}(S) := \prod_{\bar{y} \in S} \mathbb{A}_{\bar{y}} \times \prod_{\bar{y} \notin S} \mathbb{A}_{\bar{y}}^{(0)} \times \prod_{\sigma \in B_\infty} \mathbf{A}_{X_\sigma}$$

then:

$$\bigcup_{S \in \Upsilon} \mathbf{A}_{\widehat{X}}(S) = \mathbf{A}_{\widehat{X}}, \quad \bigcap_{S \in \Upsilon} \mathbf{A}_{\widehat{X}}(S) = \prod_{\bar{y} \subset \widehat{X}} \mathbb{A}_{\bar{y}}^{(0)} \times \prod_{\sigma \in B_\infty} \mathbf{A}_{X_\sigma}.$$

The following proposition establishes a nice relationship between  $\mathbf{A}_{\widehat{X}}$  and  $\mathbf{A}_X$ .

**Proposition 2.8.** *The following equality holds:*

$$\mathbf{A}_{\widehat{X}} = \mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_{\overline{K},\sigma}} \oplus \mathbf{A}_{X_\sigma}),$$

where  $\mathbf{A}_{X_{\overline{K},\sigma}}$  denotes the restricted product of  $K_{p,\sigma}$  with respect to  $\mathcal{O}_{p,\sigma}$  over the set  $X_{\overline{K},\sigma}$ .

*Proof.* It follows easily from the definitions, and the important thing to remember is that only algebraic points of  $X_\sigma$  lie on horizontal curves. This is why the first components of the bits at infinity we have  $\mathbf{A}_{X_{\overline{K},\sigma}}$  instead of  $\mathbf{A}_{X_\sigma}$ .  $\square$

*Remark 2.9.* The above definition of  $\mathbf{A}_{\widehat{X}}$  is new, but the object is very similar to the ring of completed adèles given in [9]. The difference is that [9, 25.] the spaces  $\mathbb{A}_y^{(r)}$  are obtained through some local lifting maps of  $E_{x,y}$  to  $\mathcal{O}_{x,y}$ .

*Remark 2.10.* At first glance, one might think that a reasonable definition of the adelic ring  $\mathbf{A}_{\widehat{X}}$  can be just  $\mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} \mathbf{A}_{X_\sigma}$ . With such a definition of  $\mathbf{A}_{\widehat{X}}$  we totally forget about the flags of the type  $p \in \overline{y} \subset \widehat{X}$  where  $y$  is horizontal and  $p \in X_\infty$ . So, we only add the flags of the type  $p \in X_\sigma \subset \widehat{X}$  to the usual geometric picture.

Now we give the definitions of the completed spaces  $A_\sigma$ : denote by  $K_{\overline{y}}$  the diagonal embedding of  $K_y$  inside  $\prod_{x \in \overline{y}} K_{x,\overline{y}}$ , then we put:

$$\overline{A}_{01} := \overline{\mathbf{A}}_X \cap \prod_{\overline{y} \subset \widehat{X}} K_{\overline{y}}.$$

Moreover for any  $\sigma$  let  $A_0(\sigma)$  be the diagonal embedding  $K_\sigma(X_\sigma) \hookrightarrow \prod_{p \in X_\sigma} K_{p,\sigma}$ , then:

$$A_{\widehat{01}} := \overline{A}_{01} \oplus \prod_{\sigma \in B_\infty} A_0(\sigma).$$

For  $p \in X_\sigma$  then we define  $\Delta_{p,\sigma}$  in the following way:

- If  $p$  is an algebraic point then  $\Delta_{p,\sigma}$  is the diagonal in the cartesian product  $K_{p,\overline{y}} \times K_{p,\sigma}$ , where  $\overline{y}$  is the unique horizontal curve containing  $p$  (remember that  $K_{p,\overline{y}} = K_{p,\sigma}$ ).
- of If  $p$  is transcendental, then  $\Delta_{p,\sigma} := \mathcal{O}_{p,\sigma}$ .

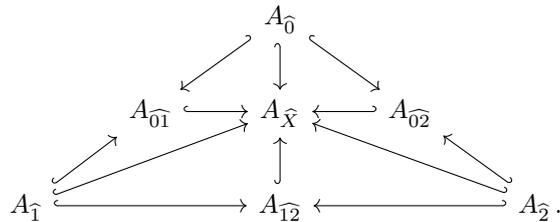
Thus we put:

$$A_{\widehat{02}} := \mathbf{A}_{\widehat{X}} \cap \left( \prod_{x \in X} K_x \times \prod_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} \Delta_{p,\sigma} \right),$$

where each  $K_x$  is naturally identified with the diagonal embedding  $K_x \hookrightarrow \prod_{\overline{y} \ni x} K_{x,\overline{y}}$ . Moreover  $A_{\widehat{0}}$  is defined as the diagonal embedding of  $K(X)$  inside  $\mathbf{A}_{\widehat{X}}$ . The other adelic subspaces are the followings:

$$A_{\widehat{12}} := \mathbf{A}_{\widehat{X}} \cap \left( \prod_{\substack{x \in \overline{y}, \\ \overline{y} \in \widehat{X}}} \mathcal{O}_{x,\overline{y}} \times \prod_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} \mathcal{O}_{p,\sigma} \right), \quad A_{\widehat{1}} := A_{\widehat{01}} \cap A_{\widehat{12}}, \quad A_{\widehat{2}} := A_{\widehat{02}} \cap A_{\widehat{12}}.$$

and the containment relations are the same as the geometric case:



**Proposition 2.11.**  $A_{\widehat{0}} = A_{\widehat{01}} \cap A_{\widehat{02}}$

*Proof.* In our proof we will use many times (and often implicitly) the fact that the adelic subspaces involved are defined by diagonal embeddings around points and along curves.

It is enough to show that  $A_0 = A_{01} \cap A_{02}$ , since the full statements about the completed spaces will follow immediately by considering the various diagonal embeddings at infinity. In particular, the only nontrivial inclusion to prove is  $A_{01} \cap A_{02} \subseteq A_0$ .

Let  $D'$  be any ample divisor on  $X$ , by [13, Proposition 5.6.3] for a positive integer  $m$  big enough we have that  $H^1(X, mD') = 0$ . So let's put  $D = mD'$  and consider the following adelic complex, which in our setting is actually a complex of  $O_K$ -modules:

$$\begin{aligned} \mathcal{A}_X(D) \quad A_0 \oplus A_1(D) \oplus A_2(D) &\xrightarrow{d^0} A_{01} \oplus A_{02} \oplus A_{12}(D) \xrightarrow{d^1} A_{012} \\ (a_0, a_1, a_2) &\longmapsto (a_0 - a_1, a_2 - a_0, a_1 - a_2) \\ (a_{01}, a_{02}, a_{12}) &\longmapsto a_{01} + a_{02} + a_{12}. \end{aligned} \tag{3}$$

At the level of the cohomology groups we have the well known equality (see for instance [17])

$$H^i(X, \mathcal{O}_X(D)) = H^i(\mathcal{A}_X(D)),$$

so, by the fact that  $H^1(X, D) = 0$ , we get  $\ker d^1 = \text{im } d^0$ . Let  $a \in A_{01} \cap A_{02}$ ; it means that there are  $a_0 \in A_0 = K(X)$ ,  $a_1 \in A_1(D)$  and  $a_2 \in A_2(D)$  such that:

$$\begin{cases} a_0 - a_1 = a \\ a_2 - a_0 = -a \\ a_1 - a_2 = 0 \end{cases} \tag{4}$$

which clearly means that  $a_1 = a_2 \in A_1(D) \cap A_2(D)$ . The first thing to notice is that a tuple in  $A_1(D) \cap A_2(D)$  is actually constant, in fact the presence of  $A_1(D)$  ensures constant blocks in the tuple correspondent to the curves of  $X$  (diagonal embedding of  $K_y$ ) whereas  $A_2(D)$  ensures constant blocks correspondent to all curves passing by to a given point (diagonal embedding of  $K_x$ ). Pick now an element  $g \in A_0$  such that  $ga_1 \in A_1 \cap A_2$ , if we show that  $A_1 \cap A_2 \subseteq A_0$ , then  $ga_1 \in A_0$ , so  $a_1 \in A_0$  and therefore by equation (4) also  $a \in A_0$ , which is the thesis.

Let  $f = (f_{x,y}) \in A_1 \cap A_2$ . Fix a point  $x_0 \in X$  lying on some horizontal curve  $y_h$  and assume that  $x_0 \in X_{\mathfrak{p}}$  where  $\mathfrak{p} \in \text{Spec } O_K$  is a prime. Notice that we can restrict to such particular  $x_0$  since the tuple  $(f_{x,y})$  is constant. Let  $y_{\mathfrak{p}}$  be any vertical curve containing  $x_0$ ; by the diagonal embedding  $\mathcal{O}_{y_{\mathfrak{p}}} \subset \prod_{x \in y_{\mathfrak{p}}} K_{x,y_{\mathfrak{p}}}$  we can identify the  $y_{\mathfrak{p}}$  component of  $f$  with a single element  $f_{x_0,y_{\mathfrak{p}}} = f_{y_{\mathfrak{p}}} \in \mathcal{O}_{y_{\mathfrak{p}}}$ . But  $f_{y_{\mathfrak{p}}} \in \mathcal{O}_x$  for any  $x \in y_{\mathfrak{p}}$ , therefore the natural projection  $\overline{f_{x_0,y_{\mathfrak{p}}}}$  in the function field  $k(y_{\mathfrak{p}})$  actually lies in  $\mathcal{O}_{y_{\mathfrak{p}},x}$  for any  $x \in y_{\mathfrak{p}}$ . But on a projective curve, a rational function which is everywhere regular is a constant, i.e.  $\overline{f_{x_0,y_{\mathfrak{p}}}}$  lies in a finite extension of  $k(\mathfrak{p})$ . Now consider the horizontal curve  $y_h$  containing  $x_0$ , then we have  $f_{x_0,y_h} = f_{x_0,y_{\mathfrak{p}}}$ . Then, pick a point  $x_1 \in y_h$  such that  $x_1 \in X_{\mathfrak{q}}$ , with  $\mathfrak{q} \neq \mathfrak{p}$ , and let  $y_{\mathfrak{q}}$  any vertical curve passing by  $x_1$ . We have the following chain of equalities:

$$f_{x_1,y_{\mathfrak{q}}} = f_{x_1,y_h} = f_{x_0,y_h} = f_{x_0,y_{\mathfrak{p}}}.$$

As before, we can easily deduce that the natural projection  $\overline{f_{x_1,y_{\mathfrak{q}}}} \in k(y_{\mathfrak{q}})$  actually lies in a finite extension of  $k(\mathfrak{q})$ . In other words we have proved that  $f$  is the diagonal image of a power series  $f = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \dots$  with  $\alpha_i$  lying in the largest ring that embeds in all the completions  $K_{\mathfrak{p}}$ , and satisfying the following properties:

- Since the natural  $\mathfrak{p}$ -projection of  $f$  must be a constant for any  $\mathfrak{p} \in B$ , then for  $j \geq 1$  the element  $\alpha_j$  is divided by any  $\mathfrak{p}$ . This clearly implies that  $\alpha_j = 0$  for  $j \geq 1$ .
- The element  $\alpha_0$  is integral in every  $K_{\mathfrak{p}}$ .

Therefore certainly  $f = \alpha_0 \in K(X)$ . □

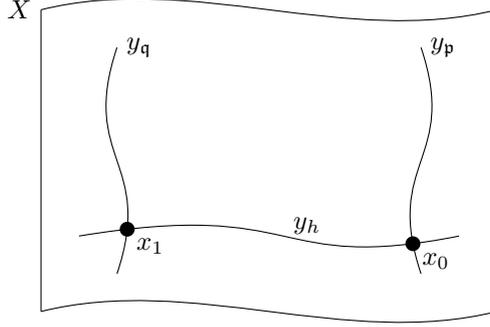


Figure 3: A visual sketch of the curves involved in the proof.

### 3 Residue theory

#### 3.1 Local multiplicative residues

For any  $b \in \widehat{B}$  we choose a (standard) character  $\psi_b: K_b \rightarrow \mathbb{T}$  such that

$$\prod_{b \in \widehat{B}} \psi_b: \mathbf{A}_{\widehat{B}} \rightarrow \mathbb{T}$$

is a character which is trivial on the diagonal embedding of  $K$  inside the adèles (see [23, Lemma 4.1.5]).

Fix a point  $x \in \widehat{X}$  lying over  $b \in \widehat{B}$  and consider completed curve  $\bar{y} \subset \widehat{X}$  containing  $x$ ; by using all local branches in  $y(x)$  we can define

$$\Omega_{x, \bar{y}}^1 := \bigoplus_{\mathfrak{z} \in y(x)} \Omega_{x, \mathfrak{z}}^1.$$

Below we describe the explicit expressions of  $\Omega_{x, \mathfrak{z}}^1$  and  $\Omega_{x, \bar{y}}^1$ , which depend on the nature of  $x$  and  $\bar{y}$ , and moreover we describe the various residue maps:

**$\bar{y}$  horizontal and  $x \in X$ .** The local field  $E_{x, \mathfrak{z}}$  is the constant field of  $K_{x, \mathfrak{z}}$  i.e.  $K_{x, \mathfrak{z}} \cong E_{x, \mathfrak{z}}((t))$  and  $[E_{x, \mathfrak{z}} : K_b] < \infty$ . In [16, 2.2] it is shown that there is an isomorphism

$$\Omega_{x, \mathfrak{z}}^1 \cong E_{x, \mathfrak{z}}((t))dt \tag{5}$$

where  $t$  is a uniformizing parameter and moreover the local residue assumes the following form independently from the choice of the isomorphism (5)

$$\begin{aligned} \text{res}_{x, \mathfrak{z}}: \Omega_{x, \mathfrak{z}}^1 &\rightarrow K_b \\ a dt &\mapsto \text{Tr}_{E_{x, \mathfrak{z}}|K_b}(a_{-1}) \end{aligned}$$

where  $a = \sum_{j \geq m} a_j t^j \in E_{x, \mathfrak{z}}((t))$ . It is shown in [18, Remark 2.9] that the residue map is continuous with respect to the topology directly induced by  $K_{x, \mathfrak{z}}$ . Moreover we put:

$$\text{res}_{x, \bar{y}} := \sum_{\mathfrak{z} \in y(x)} \text{res}_{x, \mathfrak{z}}: \Omega_{x, \bar{y}}^1 \rightarrow K_b,$$

$$\text{Cres}_{x, \bar{y}} := \psi_b \circ \text{res}_{x, \bar{y}}: \Omega_{x, \bar{y}}^1 \rightarrow \mathbb{T}$$

where  $\psi_b: K_b \rightarrow \mathbb{T}$  is the standard character.

**$\bar{y} = y$  vertical (so  $x \in X$ ).**  $K_{x, \mathfrak{z}}$  is a finite extension of the standard field  $L = K_p\{\{t\}\}$  where  $[K_p : K_b] < \infty$  and  $t$  is a uniformizing parameter for the residue field  $\bar{L} = \overline{K}_p((t))$ . Thanks to [16, 2.3] we have an isomorphism

$$\Omega_{L|K_b}^{\text{cts}} := \left( \Omega_{\mathcal{O}_L|\mathcal{O}_b}^1 \right)^{\text{sep}} \otimes_{\mathcal{O}_L} L \cong K_p\{\{t\}\}dt \tag{6}$$

where  $\Omega_{L|K_b}^{\text{cts}}$  inherits the topology directly from  $L$ . Moreover there is a continuous local residue independent from isomorphism (6):

$$\begin{aligned} \text{res}_L : \Omega_{L|K_b}^{\text{cts}} &\rightarrow K_b \\ \text{adt} &\mapsto -\text{Tr}_{K_p|K_b}(a_{-1}) \end{aligned}$$

where  $a = \sum_{j \in \mathbb{Z}} a_j t^j \in K_p\{\{t\}\}$ . By [16, Remark 2.6], we know that  $\Omega_{x,\mathfrak{z}}^1 = \Omega_{L|K_b}^{\text{cts}} \otimes_L K_{x,\mathfrak{z}}$ , so we obtain a well defined trace map

$$\text{Tr}_{K_{x,\mathfrak{z}}|L} : \Omega_{x,\mathfrak{z}}^1 \rightarrow \Omega_{L|K_b}^{\text{cts}}$$

At this point we define:

$$\text{res}_{x,\mathfrak{z}} := \text{res}_L \circ \text{Tr}_{K_{x,\mathfrak{z}}|L} : \Omega_{x,\mathfrak{z}}^1 \rightarrow K_b,$$

$$\text{res}_{x,\bar{y}} := \sum_{\mathfrak{z} \in y(x)} \text{res}_{x,\mathfrak{z}} : \Omega_{x,\bar{y}}^1 \rightarrow K_b,$$

$$\text{Cres}_{x,\bar{y}} := \psi_b \circ \text{res}_{x,\bar{y}} : \Omega_{x,\bar{y}}^1 \rightarrow \mathbb{T},$$

where  $\psi_b : K_b \rightarrow \mathbb{T}$  is the standard character.

**$\bar{y}$  completed horizontal curve and  $x = p \in y_\sigma \subset y_\infty$ .**

$$\Omega_{x,\bar{y}}^1 := \Omega_{p,\sigma}^1 = K_{p,\sigma} dt;$$

$$\text{Cres}_{x,\bar{y}} := \psi_\sigma \circ \text{res}_{p,\sigma} : \Omega_{p,\sigma}^1 \rightarrow \mathbb{T}.$$

Where in the last line,  $\text{res}_{p,\sigma}$  is the one dimensional residue on  $X_\sigma$  at the point  $p$  (see [24]) and  $\psi_\sigma : K_\sigma \rightarrow \mathbb{T}$  is the standard character of  $K_\sigma$ .

**Point at infinity  $x = p$  lying on the curve at infinity  $\bar{y} = X_\sigma$ .**

$$\text{Cres}_{p,\sigma} := \psi_\sigma \circ (-\text{res}_{p,\sigma}) : \Omega_{p,\sigma}^1 \rightarrow \mathbb{T}.$$

The detailed proofs of the independence of the various local residues maps from the parametrizations and standard fields can be found in [16].

*Remark 3.1.* The choice of the minus sign in the definition of  $\text{Cres}_{p,\sigma}$  is coherent with the main theory since  $X_\sigma$  is vertical curve on  $\widehat{X}$  in our geometric construction.

The following proposition is the extension of [18, Lemma 3.3] to the adelic case. It says that it makes sense to take the product of residues along vertical curves; moreover by looking at its proof one immediately realizes that in the definition of two dimensional adèles, “the first restricted product” along a fixed curve is a crucial operation.

**Proposition 3.2.** *Let  $\alpha \in \mathbf{A}_X$  and fix a vertical curve  $y \subseteq X_b$ . Then the series*

$$\sum_{x \in y} \text{res}_{x,y}(\alpha_{x,y} dt)$$

*converges in  $K_b$ . In particular  $\text{res}_{x,y}(\alpha_{x,y} dt) \in \mathcal{O}_b$  for all but finitely many  $x \in y$ .*

*Proof.* For simplicity let's assume that  $y$  is nonsingular. We know that  $(\alpha_{x,y})_{x \in y} \in \mathbb{A}_y^{(r)}$  for some  $r \in \mathbb{Z}$ , it means that  $(\alpha_{x,y})_{x \in y} = (t_y^r \beta_{x,y})_{x \in y}$  where  $(\beta_{x,y})_{x \in y} \in \mathbb{A}_y^{(0)}$ . Now we use the definition of  $\mathbb{A}_y^{(0)}$  to say that for any  $s > 0$  we have  $\text{res}_{x,y}(\beta_{x,y}) \in \mathfrak{p}_{K_b}^{s+m} \mathcal{O}_b$  at almost all  $x \in y$ . It follows that for any  $s > 0$ ,  $\text{res}_{x,y}(\alpha_{x,y}) \in \mathfrak{p}_{K_b}^{s+m+r} \mathcal{O}_b$  at almost all  $x \in y$ . This shows that  $\sum_{x \in y} \text{res}_{x,y}(\alpha_{x,y} dt)$  converges in  $K_b$ .  $\square$

By the universal property of the module of differential forms we have a canonical map  $\Omega_{K(X)|K}^1 \rightarrow \Omega_{x,\bar{y}}^1$ , therefore by abuse of notation, we can consider an element  $\omega \in \Omega_{K(X)|K}^1$  as an element lying in  $\Omega_{x,\bar{y}}^1$ . Moreover, by base change we know that  $\Omega_{K_\sigma(X_\sigma)|K_\sigma}^1 \cong \Omega_{K(X)|K}^1 \otimes_{K(X)} K_\sigma(X_\sigma)$ , so we have a canonical composition map:

$$\Omega_{K(X)|K}^1 \rightarrow \Omega_{K_\sigma(X_\sigma)|K_\sigma}^1 \rightarrow \Omega_{p,\sigma}^1$$

and when clear from the context we can consider  $\omega \in \Omega_{K(X)|K}^1$  as an element lying in  $\Omega_{p,\sigma}^1$ . In other words, it always makes sense to take a residue of a ‘‘rational’’ differential form  $\omega \in \Omega_{K(X)|K}^1$  for flags in  $X$  and in  $\widehat{X}$ .

**Theorem 3.3** (2D arithmetic reciprocity laws). *Let  $\omega \in \Omega_{K(X)|K}^1$  and nonzero, then:*

- (1) *Let  $x \in X$ , then  $\sum_{\bar{y} \ni x} \text{res}_{x,y}(\omega) = 0$  and  $\text{res}_{x,\bar{y}}(\omega) = 0$  for all but finitely many curves  $\bar{y}$  containing  $x$ . In particular  $\prod_{\bar{y} \ni x} \text{Cres}_{x,\bar{y}}(\omega) = 1$  and  $\text{Cres}_{x,\bar{y}}(\omega) = 1$  for all but finitely many  $x \in y$ .*
- (2) *Let  $p \in X_{\bar{K},\sigma} \subset X_\sigma$ , and let  $\bar{y}_p$  be the only completed horizontal curve containing  $p$ , then*

$$\text{Cres}_{p,\sigma}(\omega) \cdot \prod_{\bar{y} \ni p} \text{Cres}_{p,\bar{y}}(\omega) = \text{Cres}_{p,X_\sigma}(\omega) \text{Cres}_{p,\bar{y}_p}(\omega) = 1.$$

Moreover if  $p \in X_\sigma$  is transcendental, then  $\text{Cres}_{p,\sigma}(\omega) = 1$ .

- (3) *Let  $\bar{y} \subset X$  be a vertical curve or  $\bar{y} = X_\sigma$  for some  $\sigma \in B_\infty$ , then  $\sum_{x \in \bar{y}} \text{res}_{x,y}(\omega) = 0$ . In particular  $\prod_{x \in \bar{y}} \text{Cres}_{x,\bar{y}}(\omega) = 1$  and  $\text{Cres}_{x,\bar{y}}(\omega) = 1$  for all but finitely many  $x \in y$ .*
- (4) *Let  $\bar{y} \in \widehat{X}$  be a horizontal curve, then  $\prod_{x \in \bar{y}} \text{Cres}_{x,\bar{y}}(\omega) = 1$ .*

*Proof.* See [18, 2.4], [18, 5] and [18, 3] for (1), (4) and the non-archimedean part of (3) respectively. For the archimedean case of (3) see [24, Corollary of Theorem 3]. (2) Follows basically from the definitions of the local residues.  $\square$

*Remark 3.4.* Note that statements (1) and (2) of Theorem 3.3 describe reciprocity laws around a point, whereas statements (3) and (4) describe reciprocity laws for a fixed curve. Archimedean data are taken in account without any special treatment: points on  $X_\sigma$  are considered as points of  $\widehat{X}$  and achimedean fibres are considered as vertical curves on  $\widehat{X}$ . We point out that statement (2) is new and it hasn't been published anywhere before.

## 3.2 Adelic residue

In this subsection we globalise the local residues in order to get a residue at the level of completed adeles. Fix a nonzero rational 1-form  $\omega \in \Omega_{K(X)|K}^1$ , then we define the adelic residue map:

$$\begin{array}{ccc} \xi^\omega : \mathbf{A}_{\widehat{X}} & \xrightarrow{\hspace{10em}} & \mathbb{T} \\ \downarrow \Psi & & \downarrow \Psi \\ (a_{x,\bar{y}})_{\substack{x \in \bar{y}, \\ \bar{y} \subset \widehat{X}}} \times (a_{p,\sigma})_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} & \xrightarrow{\hspace{5em}} & \prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \widehat{X}}} \text{Cres}_{x,\bar{y}}(\omega a_{x,\bar{y}}) \prod_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} \text{Cres}_{p,\sigma}(\omega a_{p,\sigma}) \end{array} \quad (7)$$

Let's explain why  $\xi^\omega$  is well defined (i.e. the product (7) is convergent): along all but finitely many curves  $y \subset X$  the local residue is zero due to the restricted product with respect to the spaces  $\mathbb{A}_y^{(0)}$ . For the remaining curves we use the following arguments

- If  $y$  is horizontal it is enough to look at property (\*\*) of Lemma 2.3. It follows that the residue is 0 at all but finitely many points of  $y$ .
- If  $y$  is vertical we use Proposition 3.2.
- For curves at infinity it is enough to appeal to the 1-dimensional adelic restricted product.

In [18, Lemma 2.8, Remark 2.9] it was proved that the local residues  $\text{res}_{x,y} : \Omega_{x,y} \rightarrow K_b$  are continuous, moreover it is clear that the local residues at infinity  $\text{res}_{p,\sigma} : \Omega_{p,\sigma} \rightarrow K_\sigma$  are continuous (remember that here  $K_\sigma$  has the archimedean topology and  $K_{p,\sigma}$  the 2-dimensional topology). We are interested in the global theory of residues and we will show that the adelic residue  $\xi^\omega$  is sequentially continuous.

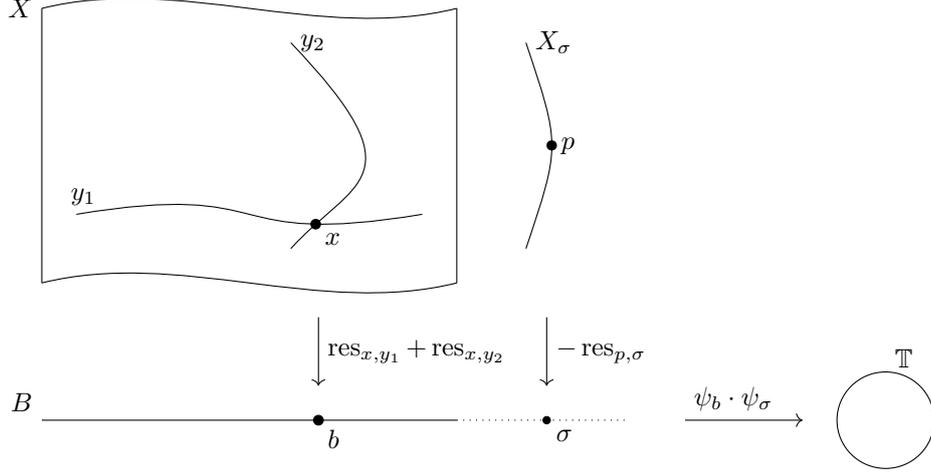


Figure 4: A graphic representation of the action of the adelic residue on 3 different flags:  $x \in y_1$ ,  $x \in y_2$  and  $p \in X_\sigma$ .

**Proposition 3.5.** *The adelic residue  $\xi^\omega$  is sequentially continuous.*

*Proof.* To prove the sequential continuity of  $\xi^\omega$  it is not necessary to consider the residues along curves at infinity because we have only a finite number of them and the 1-dimensional adelic residue is continuous. So, it is enough to discuss the schematic part of  $\xi^\omega$  which will be denoted as  $\xi_S^\omega : \mathbf{A}_X \rightarrow \mathbb{T}$ . Note that we can write  $\xi_S^\omega = \psi_S \circ \theta^\omega$  where  $\psi_S : \mathbf{A}_B \rightarrow \mathbb{T}$  is the schematic part of the 1-dimensional standard character and

$$\theta^\omega = (\theta_b^\omega)_{b \in B} : \mathbf{A}_X \rightarrow \mathbf{A}_B$$

with

$$\theta_b^\omega : \prod_{\substack{x \in y, \\ y \subset X, \\ x \rightarrow b}} K_{x,y} \rightarrow K_b$$

$$\theta_b^\omega((\alpha_{x,y})) = \sum_{\substack{x \in X_b, \\ y \ni x}} \text{res}_{x,y}(\omega \alpha_{x,y}) = \overbrace{\sum_{\substack{y \subset X_b, \\ x \in y}} \text{res}_{x,y}(\omega \alpha_{x,y})}^{(i)} + \overbrace{\sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{res}_{x,y}(\omega \alpha_{x,y})}^{(ii)} \in K_b.$$

For any  $n \in \mathbb{N}$ , let  $\alpha^{(n)} := (\alpha_{x,y}^{(n)})_{x,y} \in \mathbf{A}_X$  such that  $\lim_{n \rightarrow \infty} \alpha_{x,y}^{(n)} = 0$ . Moreover put  $\beta_{x,y}^{(n)} dt := \omega \alpha_{x,y}^{(n)}$ . Just for simplicity of notations we can assume that all curves involved in are nonsingular. We want to show that

$$\lim_{n \rightarrow \infty} \xi_S^\omega(\alpha^{(n)}) = 1.$$

Let's analyse carefully the summations (i) and (ii):

(i) We know that  $K_{x,y}$  is a finite extension of  $L = K_p\{\{t\}\}$  and we can write

$$\text{Tr}_{K_{x,y}|L}(\beta_{x,y}^{(n)}) = \sum_{i=-\infty}^{\infty} \beta_{x,y}^{(n)}(i) t^i \quad \text{for } \beta_{x,y}^{(n)}(i) \in K_p.$$

Then

$$\text{res}_{x,y}(\beta_{x,y}^{(n)} dt) = -\text{Tr}_{K_p|K_b}(\beta_{x,y}^{(n)}(-1)).$$

Since  $\lim_{n \rightarrow \infty} \beta_{x,y}^{(n)} = 0$ , there exists  $n_0 \in \mathbb{N}$  such that for  $n \geq n_0$ , we have  $\beta_{x,y}^{(n)}(-1) \in \mathcal{O}_{K_p}$ , i.e.  $\text{res}_{x,y}(\beta_{x,y}^{(n)} dt) \in \mathcal{O}_b$ . This means that

$$\lim_{n \rightarrow \infty} \sum_{\substack{y \subset X_b, \\ x \in y}} \text{res}_{x,y}(\beta_{x,y}^{(n)} dt) = 0,$$

in fact: fix the vertical curve  $y$  and consider the  $y$ -components  $\beta_y^{(n)}$  of the adelic sequence  $\beta^{(n)}$ . Since  $\beta_y^{(n)} \rightarrow 0$  as element in  $\mathbb{A}_y$ , it follows that the series converges uniformly with respect to  $n$ . Therefore it is possible to exchange the limit and the summation.

(ii) We know that  $\beta_{x,y}^{(n)} = \sum_{i \geq m} \beta_{x,y}^{(n)}(i) t^i$ , where  $\beta_{x,y}^{(n)}(i) \in E_{x,y}$  and  $E_{x,y}$  is a finite extension of  $K_b$ . Furthermore  $\lim_{n \rightarrow \infty} \beta_{x,y}^{(n)} = 0$ . We have:

$$\lim_{n \rightarrow \infty} \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{res}_{x,y}(\beta_{x,y}^{(n)} dt) = \lim_{n \rightarrow \infty} \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{Tr}_{E_{x,y}|K_b}(\beta_{x,y}^{(n)}(-1)). \quad (8)$$

Due to the adelic restricted product, for all  $n \geq n_0$  we have that  $\text{res}_{x,y}(\beta_{x,y}^{(n)}) = 0$  along all but a fixed finite set of curves  $y \subset X$ , therefore we can exchange the summation and the limit in equation (8). So we get:

$$\begin{aligned} \lim_{n \rightarrow \infty} \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{res}_{x,y}(\beta_{x,y}^{(n)} dt) &= \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \lim_{n \rightarrow \infty} \text{Tr}_{E_{x,y}|K_b}(\beta_{x,y}^{(n)}(-1)) = \\ &= \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{Tr}_{E_{x,y}|K_b} \left( \lim_{n \rightarrow \infty} \beta_{x,y}^{(n)}(-1) \right) = 0. \end{aligned}$$

We can write:

$$\lim_{n \rightarrow \infty} \xi_S^\omega(\alpha^{(n)}) = \lim_{n \rightarrow \infty} \psi_S(\theta^\omega(\alpha^{(n)})).$$

For each  $b \in B$  we have

$$\tau_b^{(n)} := \theta_b^\omega(\alpha^{(n)}) = \sum_{\substack{y \subset X_b, \\ x \in y}} \text{res}_{x,y}(\beta_{x,y}^{(n)} dt) + \sum_{\substack{x \in X_b, \\ y \ni x, \\ y \text{ horiz.}}} \text{res}_{x,y}(\beta_{x,y}^{(n)} dt)$$

and by (i) and (ii) we can conclude that:

$$\lim_{n \rightarrow \infty} \tau_b^{(n)} \in \mathcal{O}_b.$$

Finally:

$$\lim_{n \rightarrow \infty} \xi_S^\omega(\alpha^{(n)}) = \lim_{n \rightarrow \infty} \psi_S \left( \left( \tau_b^{(n)} \right)_{b \in B} \right) = \psi_S \left( \left( \lim_{n \rightarrow \infty} \tau_b^{(n)} \right)_{b \in B} \right) = 1.$$

□

From the sequential continuity of the adelic residue we can deduce a stronger version of reciprocity laws:

**Proposition 3.6.** *Fix a rational differential form  $\omega \in \Omega_{K(X)|K}^1$ . Then the following statements hold:*

- (1) *Fix a point  $x \in X$ . For any  $\alpha \in K_x$  we have  $\prod_{\bar{y} \ni x} \text{Cres}_{x,\bar{y}}(\alpha\omega) = 1$ .*
- (2) *Fix a curve  $\bar{y} \subset \widehat{X}$ . For any  $\alpha \in K_{\bar{y}}$  we have  $\prod_{x \in \bar{y}} \text{Cres}_{x,\bar{y}}(\alpha\omega) = 1$ .*

*Proof.* (1)  $K_x = K(X)\mathcal{O}_x$ , but  $\mathcal{O}_{X,x}$  is sequentially dense into its completion  $\mathcal{O}_x$ . Then the claim follows from the sequential continuity of the adelic residue and Theorem 3.3(1).

(2) Again It follows from the fact that  $K(X)$  is sequentially dense in its completion (with respect to  $y$ )  $K_y$ , the sequential continuity of the adelic residue, and Theorem 3.3(3)-(4). □

## 4 Self-duality of completed adeles

This section is entirely dedicated to the proof that the additive group  $\mathbf{A}_{\widehat{X}}$  is self-dual. We will reduce the problem to show the self-duality of  $\mathbb{A}_{\bar{y}}$  and  $\mathbf{A}_{X_\sigma}$ .

The following two lemmas characterize the characters of  $\mathbf{A}_{\widehat{X}}$ :

**Lemma 4.1.** *Let  $\chi \in \widehat{\mathbf{A}_{\widehat{X}}}$ , then  $\chi\left(\mathbb{A}_{\bar{y}}^{(0)}\right) = 1$  for all but finitely many curves  $\bar{y} \subset \widehat{X}$ . In particular if  $\beta := (\beta_{\bar{y}})_{\bar{y}} \times (\beta_\sigma)_\sigma \in \mathbf{A}_{\widehat{X}}$  we have that*

$$\chi(\beta) = \prod_{\bar{y} \subset \widehat{X}} \chi(\beta_{\bar{y}}) \prod_{\sigma \in B_\infty} \chi(\beta_\sigma).$$

(In the above formula we clearly embedded each  $\beta_{\bar{y}}$  and  $\beta_\sigma$  naturally in  $\mathbf{A}_{\widehat{X}}$ ).

*Proof.* Let  $U \subset \mathbb{T}$  be an open neighborhood of 1 which contains no subgroups of  $\mathbb{T}$  other than  $\{1\}$  and let  $V \subset \mathbf{A}_{\widehat{X}}$  be an open subset such that  $\chi(V) \subset U$ . By the definition of restricted product as direct limit with the final topology, we know that for any finite set  $S$  of completed curves in  $\widehat{X}$  the subset  $V \cap \mathbf{A}_{\widehat{X}}(S)$  is open in  $\mathbf{A}_{\widehat{X}}(S)$ . In particular by the definition of product topology, it contains an open subset of the following form:

$$W = \prod_{\bar{y} \notin S'} \mathbb{A}_{\bar{y}}^{(0)} \times \prod_{\bar{y} \in S'} W'_{\bar{y}} \times \prod_{\sigma \in B_\infty} W'_\sigma$$

where  $S'$  is another finite set of completed curves in  $\widehat{X}$  and  $W'_{\bar{y}} \subset \mathbb{A}_{\bar{y}}$ ,  $W'_\sigma \subset \mathbf{A}_{X_\sigma}$  are open. It follows that  $H := \chi\left(\prod_{\bar{y} \notin S'} \mathbb{A}_{\bar{y}}^{(0)}\right) \subset U$ , but  $H$  is a subgroup of  $\mathbb{T}$ , thus  $H = \{1\}$  by the choice of  $U$ . In particular  $\chi\left(\mathbb{A}_{\bar{y}}^{(0)}\right) = 1$  for any  $\bar{y} \notin S'$ . The last assertion of the lemma is straightforward.  $\square$

**Lemma 4.2.** *Let  $\chi_{\bar{y}} \in \widehat{\mathbb{A}_{\bar{y}}}$  and let  $\chi_\sigma \in \widehat{\mathbf{A}_{X_\sigma}}$ . If  $\chi_{\bar{y}}\left(\mathbb{A}_{\bar{y}}^{(0)}\right) = 1$  for all but finitely many curves  $\bar{y} \subset \widehat{X}$ , then*

$$\chi := \prod_{\bar{y} \subset \widehat{X}} \chi_{\bar{y}} \prod_{\sigma \in B_\infty} \chi_\sigma \in \widehat{\mathbf{A}_{\widehat{X}}}$$

*Proof.* The only thing that is not straightforward is the continuity of  $\chi$ , and there is no need to consider the fibres at infinity since they are finitely many. Let  $U \subset \mathbb{T}$  be an open neighborhood of 1 and choose  $V \subset U$  such that<sup>2</sup>  $\prod_m V \subset U$ . Now pick a finite set of completed curves  $S \subset \mathcal{Y}$  of cardinality  $m$ , and for any  $\bar{y} \in S$  take  $W_{\bar{y}} \subset \chi_{\bar{y}}^{-1}(V)$ . Then  $\prod_{\bar{y} \in S} W_{\bar{y}} \times \prod_{\bar{y} \notin S} \mathbb{A}_{\bar{y}}^{(0)}$  is contained in the preimage of  $\prod_{\bar{y}} \chi_{\bar{y}}$ .  $\square$

The following proposition is basically the “reduction argument” that allows us to restrict our attention to  $\mathbb{A}_{\bar{y}}$  and  $\mathbf{A}_{X_\sigma}$ .

**Proposition 4.3.** *The following isomorphism of topological groups holds:*

$$\widehat{\mathbf{A}_{\widehat{X}}} \cong \prod'_{\bar{y} \subset \widehat{X}} \widehat{\mathbb{A}_{\bar{y}}} \times \prod_{\sigma \in B_\infty} \widehat{\mathbf{A}_{X_\sigma}}$$

where on the right hand side the restricted product is taken with respect to the subgroups  $\left(\mathbb{A}_{\bar{y}}^{(0)}\right)^\perp \subset \widehat{\mathbb{A}_{\bar{y}}}$ .

*Proof.* Consider the map:

$$\begin{aligned} \Psi : \prod'_{\bar{y} \subset \widehat{X}} \widehat{\mathbb{A}_{\bar{y}}} \times \prod_{\sigma \in B_\infty} \widehat{\mathbf{A}_{X_\sigma}} &\rightarrow \widehat{\mathbf{A}_{\widehat{X}}} \\ (\chi_{\bar{y}})_{\bar{y} \subset \widehat{X}} \times (\chi_\sigma)_{\sigma \in B_\infty} &\mapsto \prod_{\bar{y} \subset \widehat{X}} \chi_{\bar{y}} \prod_{\sigma \in B_\infty} \chi_\sigma \end{aligned}$$

<sup>2</sup>By  $\prod$  we denote the actual complex multiplication of all elements in the open sets. In this particular case we are taking the “ $m$ -th power of  $V$ ”

where clearly we naturally considered  $\chi_{\bar{y}}, \chi_\sigma \in \widehat{\mathbf{A}_{\widehat{\mathcal{X}}}}$ . From lemmas 4.1 and 4.2 it follows immediately that  $\Psi$  is an isomorphism of groups, so we have to prove that it is continuous and open. Let  $U$  be an open neighborhood of 1 and consider the compact of  $\mathbf{A}_{\widehat{\mathcal{X}}}$ :

$$C = \prod_{\bar{y} \in S} C_{\bar{y}} \times \prod_{\bar{y} \notin S} M_{\bar{y}} \times \prod_{\sigma \in B_\infty} C_\sigma$$

where  $C_\sigma, C_{\bar{y}}$  are compacts,  $M_{\bar{y}}$  is a compact subgroup of  $\mathbb{A}_{\bar{y}}^{(0)}$ , and we assume that  $S$  has cardinality  $m$ . Then  $\mathcal{W}(C, U)$  is a basic open neighborhood of  $\mathbf{A}_{\widehat{\mathcal{X}}}$  around the identity character. Take now  $V \subset U$  such that  $\prod_{m+\#B_\infty} V \subset U$  and consider:

$$W = \prod_{\bar{y} \in S} \mathcal{W}(C_{\bar{y}}, V) \times \prod_{\bar{y} \notin S} \left( \mathbb{A}_{\bar{y}}^{(0)} \right)^\perp \times \prod_{\sigma \in B_\infty} \mathcal{W}(C_\sigma, V).$$

Then clearly  $\Psi(W) \subseteq \mathcal{W}(C, U)$ . The proof of openness is similar.  $\square$

*Remark 4.4.* So in order to show the self-duality of  $\widehat{\mathbf{A}_{\widehat{\mathcal{X}}}}$  we are reduced to show two things:

- The self-duality of  $\mathbf{A}_{X_\sigma}$ .
- There are topological and algebraic isomorphisms  $\theta_{\bar{y}} : \mathbb{A}_{\bar{y}} \rightarrow \widehat{\mathbb{A}_{\bar{y}}}$  mapping homeomorphically  $\mathbb{A}_{\bar{y}}^{(0)}$  onto  $\left( \mathbb{A}_{\bar{y}}^{(0)} \right)^\perp$  for all but finitely many completed curves.

For the self-duality of  $\mathbf{A}_{X_\sigma}$  we will use the following general results about Laurent power series over a self-dual group.

**Lemma 4.5.** *Let  $G$  be a ST ring and suppose that  $(G, +)$  is endowed with a standard character. Then  $G((t))$  has a standard character with conductor equal to 0 (see appendix A.2 to see how  $G((t))$  is topologised and for the definition of conductor).*

*Proof.* Let  $\xi$  be a standard character of  $G$ . First of all let's find explicitly a nontrivial character of  $G((t))$  which has conductor equal to 0. Consider:

$$\begin{aligned} \psi^0 : G((t)) &\rightarrow \mathbb{T} \\ \sum_{i \geq m} a_i t^i &\mapsto \xi(a_{-1}) \end{aligned}$$

Let  $\psi \in \widehat{G((t))}$ , we want to show that there exists a uniquely determined  $\alpha \in G((t))$  such that  $\psi = \psi_\alpha^0$ . Assume that  $c_\psi = i$ , for any  $b \in G$  the map  $b \mapsto \psi(bt^{i-1})$  defines a character on  $G$  that by hypothesis is equal to  $\xi_{a_0}$  for a uniquely determined  $a_0 \in G$ . So consider the character:

$$\psi^1(x) := \frac{\psi(x)}{\psi^0(xa_0t^{-i})} \quad \text{for } x \in G((t)),$$

it is easy to verify that  $\psi^1(t^{i-1}G[[t]]) = 1$ . By iterating the above argument, for any  $j \geq 1$  one finds a uniquely determined  $a_j \in G$  such that

$$\psi^{j+1}(x) := \frac{\psi^j(x)}{\psi^0(xa_jt^{-i+j})} = \frac{\psi(x)}{\psi^0\left(x \sum_{h=0}^j a_h t^{-i+h}\right)}$$

is a character trivial on  $t^{i-1-j}G[[t]]$ . By taking the limit for  $j \rightarrow \infty$  we obtain:

$$1 = \lim_{j \rightarrow \infty} \psi^j(x) = \frac{\psi(x)}{\psi^0\left(x \sum_{h \geq 0} a_h t^{-i+h}\right)}.$$

So we put  $\alpha := \sum_{h \geq 0} a_h t^{-i+h}$  and it follows that  $\psi(x) = \psi^0(x\alpha)$ .

Now we show the continuity and the openness of the map  $G((t)) \rightarrow \widehat{G((t))}$  defined by  $\alpha \mapsto \psi_\alpha^0$ . It is enough to prove the following simple things:

- (a) Given a compact  $C \subset G((t))$  and an open  $U \ni 1$  in  $\mathbb{T}$ , there exist an open set  $V \ni 0$  in  $G((t))$  such that:  $a \in V \Rightarrow aC \subseteq \psi^{-1}(U)$ .
- (b) Given an open  $U \ni 0$  in  $A$  there exist a compact  $C \subset G((t))$  and an open  $V \ni 1$  in  $\mathbb{T}$ , such that:  $aC \subseteq \psi^{-1}(V) \Rightarrow a \in U$ .

The explicit proofs of (a) and (b) are a respectively a very special case of the proofs of continuity and openness assertions of Theorem 4.7, so they are omitted here.  $\square$

**Proposition 4.6.** *The additive group  $\mathbf{A}_{X_\sigma}$  is self-dual for every  $\sigma \in B_\infty$*

*Proof.* For any point  $p \in X_\sigma$ , we have  $K_{p,\sigma} \cong K_p((t))$ , therefore we can apply Lemma 4.5 to conclude that  $K_{p,\sigma}$  is self-dual and that a standard character with conductor equal to 0 is given by  $a \mapsto \text{Cres}_{p,\sigma}(adt)$ . At this point it is enough to follow line by line the argument in Tate's thesis that shows that adèles over a number field are self-dual (see for example [22, 5.1]) to prove that  $\mathbf{A}_{X_\sigma}$  is self-dual. Actually one needs the 1-dimensional version of lemmas 4.1, 4.2 and 4.3, but recall that we have a 2-dimensional topological structure on  $K_{p,\sigma}$  and  $\mathbf{A}_{X_\sigma}$ .  $\square$

When  $\bar{y}$  is horizontal one can apply Lemma 4.5 and the explicit expression of  $\mathbb{A}_{\bar{y}}$  to show that  $\mathbb{A}_{\bar{y}}$  is self-dual, but when  $\bar{y}$  is vertical, the proof is more problematic because we don't have any nice expression of  $\mathbb{A}_{\bar{y}}$  in terms of one dimensional adèles. A deeper analysis of the proof of Lemma 4.5 unravels that the only real advantage of having the expression  $A = G((t))$ , is the ind-pro structure of  $A$  over a self-dual group  $G$  with a standard character. In general also  $\mathbb{A}_y$  has such property, and the following theorem is a generalisation of Lemma 4.5, where  $\mathbb{A}_y^{(-1)}/\mathbb{A}_y^{(0)}$  plays the role of  $G$  and  $\mathbb{A}_y^{(0)}$  plays the role of  $G[[t]]$ . We will heavily employ the topological properties described in subsection 1.3.

**Theorem 4.7.** *The additive group  $\mathbb{A}_{\bar{y}}$  is self-dual with a standard character  $\psi^0$ . Moreover  $\psi^0 \in \left(\mathbb{A}_{\bar{y}}^{(0)}\right)^\perp$  and  $\Theta_{\psi^0} \left(\mathbb{A}_{\bar{y}}^{(0)}\right) = \left(\mathbb{A}_{\bar{y}}^{(0)}\right)^\perp$ .*

*Proof.* It is enough to work with  $\mathbb{A}_y$ . For simplicity of notations let's put  $A_r := \mathbb{A}_y^{(r)}$ ,  $A := \mathbb{A}_y$  and  $t := t_y$ . Let's summarize some properties (all categorical limits are in the category of linearly topologised groups):

- (1)  $A_r$  is complete and  $A_r = \varprojlim_{j \geq 1} A_r/A_{r+j}$
- (2)  $A_r/A_{r+1}$  is locally compact and self-dual with a standard character.
- (3)  $A_r/A_{r+j}$  is locally compact for every  $j > 0$ .
- (4)  $A = \varinjlim_r A_r = \bigcup_r A_r$  and  $\bigcap_r A_r = \{0\}$ .
- (5) Any open neighborhood of 0 in  $A$  contains some  $A_r$ .

Fix a standard character  $\bar{\xi} \in \widehat{A_{-1}/A_0}$ . Then consider the following commutative diagram of topological groups with exact short sequences:

$$\begin{array}{ccccccc}
& & 0 & & 0 & & 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
0 & \longrightarrow & A_{-1}/A_0 & \longrightarrow & A_{-2}/A_0 & \longrightarrow & A_{-2}/A_{-1} & \longrightarrow & 0 \\
& & \uparrow & & \uparrow & & \uparrow & & \\
& & A_{-1} & & A_{-2} & & A_{-2} & & \\
& & \uparrow & & \uparrow & & \uparrow & & \\
& & A_0 & & A_0 & & A_{-1} & & \\
& & \uparrow & & \uparrow & & \uparrow & & \\
& & 0 & & 0 & & 0 & & 
\end{array}$$

Since the dual functor is exact on the category of LCA groups, we get the following diagram with exact short sequences:

$$\begin{array}{ccccccc}
& & 0 & & 0 & & 0 \\
& & \downarrow & & \downarrow & & \downarrow \\
0 & \longleftarrow & \widehat{A_{-1}/A_0} & \longleftarrow & \widehat{A_{-2}/A_0} & \longleftarrow & \widehat{A_{-2}/A_{-1}} & \longleftarrow & 0 \\
& & \downarrow & & \downarrow & & \downarrow & & \\
& & \widehat{A_{-1}} & & \widehat{A_{-2}} & & \widehat{A_{-2}} & & \\
& & \downarrow & & \downarrow & & \downarrow & & \\
& & \widehat{A_0} & & \widehat{A_0} & & \widehat{A_{-1}} & & 
\end{array}$$

In other words  $\bar{\xi}$  lifts to a character  $\xi^1 \in \widehat{A_{-1}}$  which is trivial on  $A_0$ , then we can lift  $\xi^1$  to a character  $\xi^2 \in \widehat{A_{-2}}$  which extends  $\xi^1$ . By iterating this process we clearly construct a character  $\xi^n \in \widehat{A_{-n}}$  extending  $\xi^1$ . Now we can define a character  $\psi : A \rightarrow \mathbb{T}$  in the following way:

$$\psi^0(a) := \xi^n(a) \quad \text{if } a \in A_n \setminus A_{n+1}.$$

By construction  $\psi^0$  is trivial on  $A_0$ . A more explicit expression of  $\psi^0$  can be given by using the identification  $A_r = t^r A_0[[t]]$ : if  $a = \sum_{i \geq r} a_i t^i \in A_r$ , then  $\psi^0(a) = \bar{\xi}(a_{-1} t^{-1})$  where  $a_{-1} t^{-1}$  is the natural projection of  $a_{-1} t^{-1}$  onto  $A_{-1}/A_0$ . We want to prove that  $\psi^0$  is a standard character for  $A$ , so that the map:

$$\begin{array}{ccc}
\Theta_{\psi^0} : A & \rightarrow & \widehat{A} \\
a & \mapsto & \psi_a^0
\end{array}$$

is an algebraic and topological isomorphism.

*Surjectivity.* Since  $\bar{\xi}$  is a standard character of  $A_{-1}/A_0$ , any other character in  $\widehat{A_{-1}}$  which is trivial on  $A_0$  is of the form  $\xi^1(g \cdot)$  for  $g \in A_{-1}$ . Consider any  $\psi \in \widehat{A}$  and let  $i = c_\psi$  the minimum integer  $i \in \mathbb{Z}$  such that  $\psi(A_i) = 1$ , note that this integer always exists thanks to (5) and the fact that  $\mathbb{T}$  has no small subgroups. Then:

$$\psi|_{A_{i-1}}(\cdot t^{-i}) = \xi^1(\cdot a_0 t^{-i}) \quad \text{for } a_0 \in A_{-1}$$

Let's define the following character

$$\psi^1(\cdot) = \frac{\psi(\cdot)}{\psi^0(\cdot a_0 t^{-i})},$$

then for any  $t^{i-1}b \in A_{i-1}$  ( $b \in A_0$ ):

$$\psi^1|_{A_{i-1}}(t^{i-1}b) = \frac{\psi(t^{i-1}b)}{\psi^0(a_0 t^{-i} t^{i-1}b)} = \frac{\xi^1(a_0 t^{-1}b)}{\psi^0(a_0 t^{-1}b)} = 1.$$

In other words  $\psi^1$  is trivial on  $A_{i-1}$ . By iterating the above process for  $j > 1$ , we find elements  $a_h \in A_{-1}$  and characters:

$$\psi^j(\cdot) = \frac{\psi(\cdot)}{\psi^0(\cdot \sum_{h=0}^j a_h t^{-i+h})}$$

which are trivial on  $A_{i-1-j}$ . Now for  $g \in A$  take the limit:

$$1 = \lim_{j \rightarrow \infty} \psi^j(g) = \frac{\psi(g)}{\psi^0(a \sum_{g \geq 0} a_h t^{-i+h})}.$$

We conclude that  $\psi(\cdot) = \psi^0(\cdot \alpha)$  for  $\alpha := \sum_{h \geq 0} a_h t^{-i+h}$ . The partial sums defining  $\alpha$  form a Cauchy sequence in  $A_{-1}$ , which is complete, so  $\alpha$  is actually an element of  $A_{-1}$ .

*Injectivity.* For every  $a \in A \setminus 0$ , there exists  $r \in \mathbb{Z}$  such that  $\ker \psi_a$  is trivial on  $A_r$  but not on  $A_{r-1}$ .

*Continuity.* We have to show that given a compact  $K \subset A$  and an open  $U \ni 1$  in  $\mathbb{T}$ , there exist an open set  $V \ni 0$  in  $A$  such that:  $\psi(VK) \subseteq U$ . Since  $K$  is contained in some  $A_m$ , by simplicity we can “shift”  $K$  thanks to the multiplication by  $t^{m-1}$  and assume  $K \subset A_{-1}$ . Then  $K = \varprojlim_j K_j$  with  $K_j \in A_{-1}/A_j$ . Now, since  $\bar{\xi}$  is a standard character for  $A_{-1}/A_0$ , it is not difficult to show by induction that the multiplication in  $A$  and the character  $\psi^0$  induce an algebraic and topological isomorphism  $A_{-1}/A_j \cong \widehat{A_{-j}/A_1}$  for any  $j \geq 0$ . Thus we induce perfect pairing of LCA groups:

$$e_j : A_{-1}/A_j \times A_{-j}/A_1 \rightarrow \mathbb{T}.$$

Consider the orthogonal complement  $W_j = K_j^\perp := \{a \in A_{-j}/A_1 : e_j(K_j, a) = 1\}$ , then  $W_j$  is open in  $A_{-j}/A_1$ . Let  $V_j \subset A_{-j}$  be the lift of  $W_j$ , it follows that the open set  $V = \bigcup_j V_j$  is the open set we were looking for.

*Openess.* We have to show that given an open  $U \ni 0$  in  $A$  there exist a compact  $K \subset A$  and an open  $V \ni 1$  in  $\mathbb{T}$ , such that  $aK \subseteq \psi^{-1}(V) \Rightarrow a \in U$ . The open set  $U$  is contained in a basic open subgroup  $\sum' U_i t^i$  where we assume that  $U_i = A_0$  for  $i \geq m$ . Since  $A_{-1}/A_0$  has a standard character, for any  $i < m$  there exists a compact  $C_i \subset A_{-1}/A_0$  and an open  $V_i \ni 1$  in  $\mathbb{T}$  such that:

$$\bar{\xi}(\bar{a}C_i) \subset V_i \Rightarrow \bar{a} \in \overline{U_i t^{-1}} \subset A_{-1}/A_0.$$

Since  $\mathbb{T}$  has no small subgroups, we can actually choose  $\bar{V}_i$  in a way that

$$\bar{\xi}(\bar{a}C_i) = 1 \Rightarrow \bar{a} \in \overline{U_i t^{-1}}.$$

Now, since for any  $r \geq 1$  we have a surjective homomorphisms of LCA groups  $A_{-1}/A_r \rightarrow A_{-1}/A_0$ , we can lift  $\bar{C}_i$  to  $C_i^r \in A_{-1}/A_r$  which in turn gives  $C_i = \varprojlim_r C_i^r$  compact in  $A_{-1}$ . We put  $K_i = C_i t \in A_0$ . For  $i \geq m$  we choose  $K_i = 0$ , so we construct the compact set  $K = \sum_i K_i t^{-i}$  in  $A$ . It is easy to show that  $K$  and a small enough  $V \subset \mathbb{T}$  containing 1 satisfy the requirements needed to show openness.

Clearly  $\Theta_{\psi^0}(A_0) \subseteq (A_0)^\perp$ . Let  $\psi_a^0 \notin (A_0)^\perp$ , then there exists  $b \in A_0$  such that  $\psi^0(ab) \neq 1$ , but this means that  $a \notin A_0$  otherwise we would have  $\psi^0(ab) = 1$ .  $\square$

**Corollary 4.8.**  $\mathbf{A}_{\widehat{X}}$  is self-dual.

*Proof.* The proof follows directly from Propositions 4.3, 4.6 and Theorem 4.7. For more clarity, see also Remark 4.4.  $\square$

## 5 Properties of the adelic differential pairing

Fix a nonzero rational differential form  $\omega \in \Omega_{K(X)|X}^1$ , then the *adelic differential pairing (associated to  $\omega$ )* is defined as:

$$\begin{aligned} d_\omega : \mathbf{A}_{\widehat{X}} \times \mathbf{A}_{\widehat{X}} &\rightarrow \mathbb{T} \\ (\alpha, \beta) &\mapsto \xi^\omega(\alpha\beta). \end{aligned}$$

For any subset  $S \subseteq \mathbf{A}_{\widehat{X}}$  we define the *orthogonal complement of  $S$  with respect to  $d_\omega$* :

$$S^\perp := \{\beta \in \mathbf{A}_{\widehat{X}} : d_\omega(S, \beta) = 1\}. \quad (9)$$

The operator  $\perp$  in this section shouldn't be confused with the one for topological groups and their duals.

**Proposition 5.1.** *The map  $d_\omega$  has the following properties:*

- (1) *It is symmetric and sequentially continuous.*
- (2) *For any couple of subgroups  $H_1, H_2 \subseteq \mathbf{A}_{\widehat{X}}$  we have  $H_1^\perp \cap H_2^\perp = (H_1 + H_2)^\perp$ .*

*Proof.* (1) Symmetry is obvious, sequential continuity follows easily from the fact that  $\xi^\omega$  and the product are sequentially continuous.

(2) If  $h \in H_1^\perp \cap H_2^\perp$ , then  $d_\omega(h, H_1 + H_2) = d(h, H_1) + d(h, H_2) = 1$ , so one inclusion is proved. Vice versa assume that  $h \in (H_1 + H_2)^\perp$ , then  $d(h, H_i) = 0$  for  $i = 1, 2$ , so we have also the other inclusion.  $\square$

Now we show that the spaces  $A_{\widehat{01}}$  and  $A_{\widehat{02}}$  are equal to their orthogonal complements. Compare these results with the “geometric counterpart” in [10].

**Theorem 5.2.**  $A_{\widehat{01}}^\perp = A_{\widehat{01}}$ .

*Proof.* We show the equality by showing two inclusions. First we prove that  $A_{\widehat{01}} \subseteq A_{\widehat{01}}^\perp$ . It is essentially a consequence of our reciprocity laws for completed arithmetic surfaces. We have to show that for any  $\alpha, \beta \in A_{\widehat{01}}$ ,  $d_\omega(\alpha, \beta) = \xi^\omega(\alpha\beta) = 1$ . Let  $a = \alpha\beta$ , then

$$\xi^\omega(a) = \prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \widehat{X}}} \text{Cres}_{x, \bar{y}}(\omega a_{x, \bar{y}}) \prod_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} \text{Cres}_{p, \sigma}(\omega a_{p, \sigma}).$$

The first product is equal to 1 thanks to Proposition 3.6(2); the second product is 1 thanks to the one dimensional reciprocity law.

Next we show the inclusion  $A_{\widehat{01}}^\perp \subseteq A_{\widehat{01}}$ . We take an element  $a = (a_{\bar{y}}) \times (a_\sigma) \in A_{\widehat{01}}^\perp$ . We need to show that  $a_{\bar{y}} \in K_{\bar{y}}$  and  $a_\sigma \in \mathbb{A}_0(\sigma)$ . We consider 3 cases.

**Curves at infinity.** Pick any  $g \in \mathbb{A}_0(\sigma) \subset A_{\widehat{01}}$ , then since  $a \in A_{\widehat{01}}^\perp$

$$d_\omega(a, g) = \prod_{p \in X_\sigma} \text{Cres}_{p, \sigma}(a_{p, \sigma} g \omega) = 1.$$

If  $\psi$  is the standard character of  $K_\sigma$ , it follows that

$$\sum_{p \in X_\sigma} \text{res}_{p, \sigma}(a_{p, \sigma} g \omega) \in \ker \psi = \frac{1}{2}\mathbb{Z} + \mathbb{R}i, \quad \forall g \in A_0(\sigma). \quad (10)$$

By equation (10) for any  $\lambda \in \mathbb{R}$  we have

$$\sum_{p \in X_\sigma} \text{res}_{p, \sigma}(a_{p, \sigma} \lambda \omega) = \lambda \sum_{p \in X_\sigma} \text{res}_{p, \sigma}(a_{p, \sigma} \omega) \in \frac{1}{2}\mathbb{Z} + \mathbb{R}i.$$

It follows that  $\sum_{p \in X_\sigma} \text{res}_{p, \sigma}(a_{p, \sigma} \omega) = 0$ . We can replace  $a_\sigma$  with  $a_\sigma h$  for any  $h \in A_0(\sigma)$  to get  $\sum_{p \in X_\sigma} \text{res}_{p, \sigma}(a_{p, \sigma} h \omega) = 0$ . In other words  $a_\sigma$  lies in the orthogonal complement of  $A_0(\sigma)$  with respect to the pairing:

$$\begin{aligned} T_\omega : \mathbf{A}_{X_\sigma} \times \mathbf{A}_{X_\sigma} &\rightarrow \mathbb{C} \\ ((\alpha_{p, \sigma}), (\beta_{p, \sigma})) &\mapsto \sum_{p \in X_\sigma} \text{res}_{p, \sigma}(\alpha_{p, \sigma} \beta_{p, \sigma} \omega) \end{aligned}$$

But we know that  $\mathbb{A}_0(\sigma)$  is equal to its orthogonal complement (with respect to  $T_\omega$ ). Such a result was proved for number fields in [23, Theorem 4.1.4], but see for example [7, Theorem 2.21] for the function field case. Therefore we conclude that  $a_\sigma \in A_0(\sigma)$ .

**$\bar{y}$  horizontal.** We know that  $\mathbb{A}_{\bar{y}} = \mathbf{A}_{\bar{y}}((t_y))$ , where  $t_y$  is a local parameter for  $K_{\bar{y}} \subset A_{\widehat{01}}$  and therefore any  $a_{\bar{y}}$  has the following expression:

$$\mathbb{A}_{\bar{y}} = \mathbf{A}_{\bar{y}}((t)) \ni a_{\bar{y}} = \sum_{i \geq m} a_i t_y^i \quad \text{with } a_i \in \mathbf{A}_{\bar{y}}.$$

We can also take  $\omega = f dt_y$ . Then for any  $r \in \mathbb{Z}$  and any  $c \in k(y)$ :

$$d_\omega(a_{\bar{y}}, c f^{-1} t_y^r) = \prod_{x \in \bar{y}} \text{Cres}_{x, \bar{y}}(a_{x, \bar{y}} t_y^r c dt_y) = \xi^{dt_y}(a_{\bar{y}} t_y^r c) = 1. \quad (11)$$

Then  $\xi^{dt_y}(a_{\bar{y}} t_y^r c)$  is a standard character of the one dimensional adeles  $\mathbf{A}_{\bar{y}}$  calculated at  $ca_{-r-1}$ . Since equation (11) holds for every  $r \in \mathbb{Z}$ , and  $k(y)$  is equal to  $k(y)^\perp$  in  $\mathbf{A}_{\bar{y}}$  (again [23, Theorem 4.1.4]), we can conclude that  $a_i \in k(y)$  for every  $i$ . This means that  $a_{\bar{y}} \in K_{\bar{y}}$ .

$\bar{y} = y$  **vertical**. Let  $\bar{t} \in k(y)$  be a uniformizing parameter and consider a lift  $t \in \mathcal{O}_{X,y}$ . Put  $\omega = f dt$  and let  $L = K_p\{\{t\}\}$  a standard subfield of  $K_{x,y}$ . We know that there exists an integer  $s$  such that  $\text{Tr}_{K_p|K_b}(\mathfrak{p}_{K_p}^s) \subseteq \mathfrak{p}_{K_b}$ . Fix  $r \in \mathbb{Z}$  such that  $\text{Tr}_{K_{x,y}|L}(p^r a_{x,y}) \in \mathfrak{p}_L^s$ . For any  $m \in \mathbb{Z}$  we have  $f^{-1}p^r t^m \in K_y \subset A_{\widehat{01}}$ , so since  $a \in A_{\widehat{01}}^\perp$  we obtain that

$$d(a, f^{-1}p^r t^m) = \sum_{x \in y} \text{res}_{x,y}(p^r a_{x,y} \cdot t^m dt) \in \mathcal{O}_b.$$

Since  $\text{Tr}_{K_{x,y}|L}(p^r a_{x,y}) \in \mathfrak{p}_L^s$  and  $\text{Tr}_{K_p|K_b}(\mathfrak{p}_{K_p}^s) \subseteq \mathfrak{p}_{K_b}$ :

$$\sum_{x \in y} \overline{\text{res}_{x,y}(p^r a_{x,y} \cdot t^m dt)} = 0$$

Now we apply [16, Corollary 2.23] to write

$$\begin{aligned} 0 &= \sum_{x \in y} \overline{\text{res}_{x,y}(p^r a_{x,y} \cdot t^m dt)} = \sum_{x \in y} \overline{\text{res}_{x,y}(p^r a_{x,y} \cdot t^m dt)} = \\ &= \sum_{x \in y} e_{x,y} \text{res}_{x,y}^{(1)}(\overline{p^r a_{x,y} \cdot t^m dt}) = \sum_{x \in y} \text{res}_{x,y}^{(1)}(e_{x,y} \overline{p^r a_{x,y} \cdot t^m dt}) \end{aligned}$$

where:

- $\text{res}_{x,y}^{(1)} : E_{x,y} \rightarrow k(b)$  is the one dimensional residue on  $E_{x,y}$ .
- $e_{x,y} := e(K_{x,y}|K_b)$  is the ramification degree.

The above relation holds for any  $m \in \mathbb{Z}$ , and moreover we apply the same one-dimensional argument used in the case of the curves at infinity to conclude that  $k(y)$  is equal to  $k(y)^\perp$  in  $\mathbf{A}_y$ . It follows that  $(\overline{a_{x,y}})_{x \in y} \in k(y)$ , therefore  $a_y \in K_y$ .  $\square$

Before proving that  $A_{\widehat{02}}$  is self-orthogonal we need to study with more detail the structure of a neighborhood of a point  $x \in X$  such that  $\varphi(x) = b$ . Let's denote with  $\text{Spec}^1 \mathcal{O}_x$  the set of prime ideals of height 1 in  $\mathcal{O}_x$ , then a curve  $y$  passing by  $x$  corresponds to the set of local branches  $y(x) \subset \text{Spec}^1 \mathcal{O}_x$ . But there might be some elements  $\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x$  which don't correspond to any curve passing by  $x$ , those are exactly those ideals:

$$\mathfrak{T}(x) := \{\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x : \mathfrak{q} \cap \mathcal{O}_{X,x} = (0)\}.$$

The elements of  $\mathfrak{T}(x)$  are called *transcendental curves (passing by  $x$ )*.

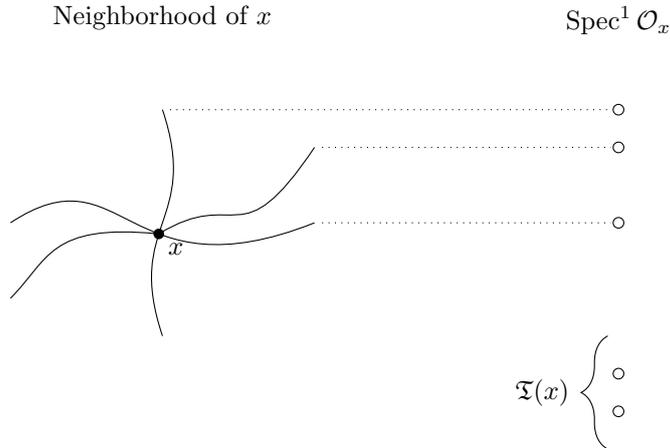


Figure 5: A visual representation of the correspondence between prime ideals of  $\mathcal{O}_x$  and curves passing by  $x$ . For simplicity we assumed that the curves are nonsingular at  $x$ , hence  $y(x)$  is exactly a point in  $\text{Spec} \mathcal{O}_x$  for any  $y$ .

Also for any  $\mathfrak{q} \in \mathfrak{T}(x)$  it is possible to construct a 2-dimensional local field  $K_{x,\mathfrak{q}}$  and the residues  $\text{res}_{x,\mathfrak{q}} : \Omega_{x,\mathfrak{q}} \rightarrow K_b$ ,  $\text{Cres}_{x,\mathfrak{q}} : \Omega_{x,\mathfrak{q}} \rightarrow \mathbb{T}$  in the usual way. But transcendental curves have the following pathological behaviour:

**Lemma 5.3.** Fix  $\omega \in \Omega_{K(X)|K}^1$  and let  $\mathfrak{q} \in \mathfrak{T}(x)$ , then  $\text{Cres}_{x,\mathfrak{q}}(\omega) = 1$ . Moreover if  $g \in K'_x$ , then  $\text{Cres}_{x,\mathfrak{q}}(g\omega) = 1$ .

*Proof.* The first claim follows immediately from the fact that  $K(X) \subseteq (\mathcal{O}_x)_{\mathfrak{q}}$ . For the second one it is enough to notice that  $K_x = K(X)\mathcal{O}_x$  is sequentially dense in  $K'_x$  and use the first part of the lemma.  $\square$

The presence of transcendental curves is a subtlety in the adelic theory. In fact, in general  $K_x$  is obviously a proper subring of  $K'_x$ , but the following result from commutative algebra ensures that  $K_x$  and  $K'_x$  coincide if and only if there are no transcendental curves passing by  $x$ .

**Proposition 5.4.** Let  $A$  be a Noetherian, regular, local domain and let  $\widehat{A}$  be the completion with respect to its maximal ideal. Then the product  $\widehat{A}\text{Frac } A$  is a field if and only if for any nonzero prime  $\mathfrak{q} \subset \widehat{A}$ ,  $\mathfrak{q} \cap A \neq (0)$ .

*Proof.* Since  $A$  is regular and local, also  $\widehat{A}$  is regular and local, which implies that  $\widehat{A}$  and  $\widehat{A}\text{Frac } A$  are integral domains as well. It follows that  $\widehat{A} \otimes_A \text{Frac } A \cong \widehat{A}\text{Frac } A$ . Then it is well known (e.g. [14, pag. 47]) that we have an homeomorphism:

$$\text{Spec}(\widehat{A} \otimes_A \text{Frac } A) \cong S := \left\{ \mathfrak{q} \in \text{Spec } \widehat{A} : \mathfrak{q} \cap A = (0) \right\}. \quad (12)$$

( $\Rightarrow$ )  $\widehat{A} \otimes_A \text{Frac } A$  contains only a prime ideal, the trivial one, so by the homeomorphism (12),  $S$  contains only one element, which is  $(0)$ . ( $\Leftarrow$ ) If  $S$  contains only  $(0)$ , then by the homeomorphism (12) the only prime ideal of  $\widehat{A} \otimes_A \text{Frac } A$  is  $(0)$ , which means that  $\widehat{A} \otimes_A \text{Frac } A$  is a field.  $\square$

**Corollary 5.5.** Fix a closed point  $x \in X$ , then  $K_x = K'_x$  if and only if there are no transcendental curves passing by  $x$ .

*Proof.* By definition  $K_x = K(X)\mathcal{O}_x$  is the smallest ring containing  $K(X)$  and  $\mathcal{O}_x$ , so the claim follows from Proposition 5.4.  $\square$

Now let's put

$$\mathbf{A}_{X,x} := \mathbf{A}_X \cap \prod_{y \ni x} K_{x,y},$$

$$\mathbf{A}'_{X,x} := \prod'_{\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x} K_{x,\mathfrak{q}} \quad \text{with resp. to } \mathcal{O}_{x,\mathfrak{q}},$$

and note that  $\mathbf{A}'_{X,x} \supseteq \mathbf{A}_{X,x}$ . Lemmas 5.8 and 5.9 below will be used to show the inclusion  $A_{02}^{\perp} \subseteq A_{02}$ . The first one will be a modified version of [12, Lemma 3.3], so we present a proof. The second one will be just [12, Lemma 3.4] rewritten with our notation, so for its proof we remand the reader to the appropriate reference.

*Remark 5.6.* The paper [12] shows only some local calculations regarding residues on the space  $\mathbf{A}'_{X,x}$ . Moreover the space denoted as  $K_x$  in [12] is exactly our  $K'_x$ .

**Lemma 5.7.** Let  $F$  be a complete discrete valuation field, then:

$$\text{Frac}(\mathcal{O}_F[[t]]) = \left\{ \sum_{i \geq m} a_i t^i \in F((t)) : \inf_i v(a_i) > -\infty \right\}.$$

*Proof.* ( $\supseteq$ ) Let  $f = \sum_{i \geq m} a_i t^i$  such that  $k = \inf_i v(a_i)$ , and let  $\varpi$  be a uniformizing parameter of  $F$ . Then  $\varpi^{-k} f \in \mathcal{O}_F((t))$  and the required inclusion follows easily.

( $\subseteq$ ) Let  $f \in \mathcal{O}_F[[t]] \setminus \{0\}$ , then for  $r, s \geq 0$  we can obviously write  $f = \varpi^r t^s \sum_{i \geq 0} b_i t^i$  such that  $b_0 \in \mathcal{O}_F^\times$ . It follows that  $\sum_{i \geq 0} b_i t^i$  is invertible, therefore we only need to enlarge  $\mathcal{O}_F[[t]]$  with the inverses of the elements of the type  $\varpi^r t^s$ ; but such inverses clearly satisfy the required condition about the infimum.  $\square$

The morphism  $\varphi : X \rightarrow B$  sending  $x$  to  $b$  induces a finite ring extension  $\mathcal{O}_b[[t]] \hookrightarrow \mathcal{O}_x$ , therefore from now on we can always identify  $\mathcal{O}_b[[t]]$  with its image in  $\mathcal{O}_x$  when  $\varphi(x) = b$ .

**Lemma 5.8.** *Assume that  $\mathcal{O}_x = \mathcal{O}_b[[t]]$ . Fix a rational differential form  $\omega \in \Omega_{K(X)|K}^1$  and let  $a = (a_{x,\mathfrak{q}}) \in \mathbf{A}'_{X,x}$  such that:*

$$\prod_{\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x} \text{Cres}_{x,\mathfrak{q}}(ga_{x,\mathfrak{q}}\omega) = 1 \quad \text{for any } g \in K'_x, \quad (13)$$

then  $a \in K'_x$ .

*Proof.* There is a well known classification result for the elements  $\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_b[[t]] = \text{Spec}^1 \mathcal{O}_x$  (see for example [19, Lemma 5.3.7]):

- $\mathfrak{q} = \mathfrak{q}_v := \pi_b \mathcal{O}_x$ , where  $\pi_b$  is the uniformizing parameter of  $\mathcal{O}_x$ . This is the only prime ideal such that  $K_{x,\mathfrak{q}_v}$  is of mixed characteristic.
- $\mathfrak{q} = h_{\mathfrak{q}} \mathcal{O}_x$  where  $h_{\mathfrak{q}} \in \mathcal{O}_b[[t]]$  is an irreducible Weierstrass polynomial, i.e.  $h_{\mathfrak{q}} = t^d + a_1 t^{d-1} + \dots + a_d$  with  $a_i \in \mathfrak{p}_{K_b}$ .

Without loss of generality we may assume that  $a_{x,\mathfrak{q}} \in \mathcal{O}_{x,\mathfrak{q}}$  for any  $\mathfrak{q} \neq \mathfrak{q}_v$  since multiplying  $(a_{x,\mathfrak{q}})$  by any nonzero element in  $K'_x$  amounts to an equivalent problem. Moreover, for the same reason we can also assume for simplicity that  $\omega = 1dt$ .

For any  $\mathfrak{q} \neq \mathfrak{q}_v$  and any uniformizing parameter  $\pi_{\mathfrak{q}}$  for the 2-dimensional local fields  $K_{x,\mathfrak{q}}$ , we can choose the following isomorphism:

$$\begin{aligned} K_{x,\mathfrak{q}} &\xrightarrow{\cong} E_{x,\mathfrak{q}}((h_{\mathfrak{q}})) \\ \pi_{\mathfrak{q}} &\mapsto h_{\mathfrak{q}}(t). \end{aligned}$$

In other words  $t$  can be identified with a root of the polynomial equation  $h_{\mathfrak{q}}(t) = \pi_{\mathfrak{q}}$ . By Hensel's lemma we deduce that such a root exists and it is integral, thus we can write:

$$t = \sum_{i \geq 0} c_i \pi_{\mathfrak{q}}^i \quad \text{with } c_i \in E_{x,\mathfrak{q}}.$$

The following two easy results are fundamental:

- (i)  $h_{\mathfrak{q}} \in \mathcal{O}_{x,\mathfrak{q}'}$  for any  $\mathfrak{q}' \neq \mathfrak{q}, \mathfrak{q}_v$ . This is obvious from the definition of  $\mathcal{O}_{x,\mathfrak{q}'}$ .
- (ii)  $t \in \mathcal{O}_{x,\mathfrak{q}'}$  for any  $\mathfrak{q}' \neq \mathfrak{q}$ . Assume by contradiction that  $t \notin \mathcal{O}_{x,\mathfrak{q}'}$  and let  $h_{\mathfrak{q}} = t^d + a_1 t^{d-1} + \dots + a_d$ , then by (i):

$$\begin{aligned} 0 &= v_{x,\mathfrak{q}'}(t^d + a_1 t^{d-1} + \dots + a_d) = \min \{v_{x,\mathfrak{q}'}(t^d), v_{x,\mathfrak{q}'}(a_1 t^{d-1}), \dots, v_{x,\mathfrak{q}'}(a_d)\} = \\ &= \min \{dv_{x,\mathfrak{q}'}(t), (d-1)v_{x,\mathfrak{q}'}(t), \dots, 0\} = dv_{x,\mathfrak{q}'}(t) < 0 \end{aligned}$$

which cannot be true.

If for any  $\mathfrak{q}' \neq \mathfrak{q}_v$  we write

$$a_{x,\mathfrak{q}'} = \sum_{i \geq 0} a_{i,\mathfrak{q}'} \pi_{\mathfrak{q}'}^i, \quad a_{i,\mathfrak{q}'} \in E_{x,\mathfrak{q}'},$$

by (i) – (ii) and equation (13), for any  $n \geq 0$  we have

$$\prod_{\mathfrak{q}' \in \text{Spec}^1 \mathcal{O}_x} \text{Cres}_{x,\mathfrak{q}'}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}'} \omega) = \text{Cres}_{x,\mathfrak{q}}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}} \omega) \cdot \text{Cres}_{x,\mathfrak{q}_v}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}_v} \omega) = 1.$$

Therefore, we have the equality

$$\text{Cres}_{x,\mathfrak{q}}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}} \omega) = \text{Cres}_{x,\mathfrak{q}_v}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}_v} \omega)^{-1}, \quad (14)$$

but by definition

$$\text{Cres}_{x,\mathfrak{q}}(h_{\mathfrak{q}}^{-1} t^n a_{x,\mathfrak{q}} \omega) = \psi_b(\text{Tr}_{E_{x,\mathfrak{q}}|K_b}(c_0^n a_{0,\mathfrak{q}})). \quad (15)$$

Since we can take  $1, c_0, \dots, c_0^{\deg h_{\mathfrak{q}} - 1}$  as a basis of  $E_{x,\mathfrak{q}}$  over  $K_b$ , equations (14) and (15) imply that  $\text{Tr}_{E_{x,\mathfrak{q}}|K_b}(\lambda a_{0,\mathfrak{q}})$  is determined by  $a_{x,\mathfrak{q}_v}$  for any  $\lambda \in E_{x,\mathfrak{q}}$ . By using non-degeneracy of the trace pairing

$$\begin{aligned} E_{x,\mathfrak{q}} \times E_{x,\mathfrak{q}} &\rightarrow K_b \\ (u, s) &\mapsto \text{Tr}_{E_{x,\mathfrak{q}}|K_b}(us) \end{aligned}$$

we conclude that the element  $a_{0,\mathfrak{q}}$  is uniquely determined by  $a_{x,\mathfrak{q}_v}$ . We can conduct the same calculations for  $h_{\mathfrak{q}}^{-i-1}t^n a_{x,\mathfrak{q}}$ , to see that  $a_{i,\mathfrak{q}}$  is determined by  $a_{x,\mathfrak{q}_v}$  for any positive integer  $i$ . It leads us to a conclusion that  $a_{x,\mathfrak{q}}$  is uniquely determined by  $a_{x,\mathfrak{q}_v}$  for any  $\mathfrak{q} \neq \mathfrak{q}_v$ .

So, we are reduced to show that  $a_{x,\mathfrak{q}_v}$  is in  $K'_x$ . Recall that  $K_{x,\mathfrak{q}_v} \cong K_b\{\{t\}\}$ , so we can write

$$a_{x,\mathfrak{q}_v} = \sum_{i \in \mathbb{Z}} a_{i,\mathfrak{q}_v} t^i, \quad a_{i,\mathfrak{q}_v} \in K_b.$$

Now, by putting  $\mathfrak{p}_0 = t\mathcal{O}_x$  and reasoning similarly as above we obtain

$$\text{Cres}_{x,\mathfrak{q}_v}(t^{i-1}a_{x,\mathfrak{q}_v}\omega)^{-1} = \text{Cres}_{x,\mathfrak{p}_0}(t^{i-1}a_{x,\mathfrak{p}_0}\omega) = 1, \quad \text{for all } i \geq 1.$$

It means that  $a_{-i,\mathfrak{q}_v}^{-1} \in \mathcal{O}_b$  for any  $i \geq 1$ . By definition of  $K_b\{\{t\}\}$ , we know that there exists  $N > 0$  such that  $a_{-i,\mathfrak{q}_v} \in \mathcal{O}_b$  for  $i \geq N$ . In other words if  $i \geq N$  and  $a_{-i,\mathfrak{q}_v} \neq 0$ , then  $a_{-i,\mathfrak{q}_v} \in \mathcal{O}_b^\times$ . Since  $\lim_{j \rightarrow -\infty} a_{j,\mathfrak{q}_v} = 0$ , we conclude that it has to exist  $M > 0$  such that  $a_{-i,\mathfrak{q}_v} = 0$  for  $i \geq M$ . This proves that  $a_{x,\mathfrak{q}_v} \in K_b((t))$ . By hypothesis  $a_{x,\mathfrak{q}_v} \in K_{x,\mathfrak{q}_v}$ . Since  $K_{x,\mathfrak{q}_v}$  is of mixed characteristic, the valuations on the coefficients of  $a_{x,\mathfrak{q}_v}$  are bounded from below, therefore we can use Lemma 5.7 to conclude that  $a_{x,\mathfrak{q}_v} \in \text{Frac}(\mathcal{O}_b[[t]]) = K'_x$ .  $\square$

Let  $x \in X$  such that  $\varphi(x) = b$ , then we put  $\mathcal{O}_x^\# := \mathcal{O}_b[[t]] \subseteq \mathcal{O}_x$  (recall that  $\mathcal{O}_b[[t]]$  is canonically embedded in  $\mathcal{O}_x$ ). For any prime  $u \in \text{Spec}^1 \mathcal{O}_x^\#$  we have the 2-dimensional local field  $K_{x,u}^\#$  obtained by the usual process of completion/localization. In general we can construct all local adelic objects relative to the flags  $x \in u \in \text{Spec}^1 \mathcal{O}_x^\#$ . Such objects arising from the special ring  $\mathcal{O}_x^\#$  will be marked with the symbol  $\#$  to distinguish them from the usual ones. Let  $\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x$  be a prime sitting over  $u$ , then we have a finite field extension  $K_{x,\mathfrak{q}}|K_{x,u}^\#$  and a trace map  $\text{Tr}_{K_{x,\mathfrak{q}}|K_{x,u}^\#}$  which extends directly at the level of differential forms:

$$\begin{aligned} \text{Tr}_{K_{x,\mathfrak{q}}|K_{x,u}^\#} : \Omega_{x,\mathfrak{q}}^1 &\rightarrow \Omega_{x,u}^{1,\#} \\ f dt &\mapsto \text{Tr}_{K_{x,\mathfrak{q}}|K_{x,u}^\#}(f) dt \end{aligned}$$

Such a map is exactly the abstract trace map for differential forms defined in [16] and mentioned in section 3. We recall that in [16] it is also proved that the residue is functorial with respect to the trace, which in our case means that  $\text{res}_{x,\mathfrak{q}} = \text{res}_{x,u}^\# \circ \text{Tr}_{K_{x,\mathfrak{q}}|K_{x,u}^\#}$ . The local trace map defined above can be further generalized to an adelic trace:

$$\begin{aligned} \text{Tr}_x : \mathbf{A}'_{X,x} &\rightarrow (\mathbf{A}'_{X,x})^\# \\ (a_{x,\mathfrak{q}})_{\mathfrak{q}} &\mapsto \left( \sum_{\mathfrak{q}|u} \text{Tr}_{K_{x,\mathfrak{q}}|K_{x,u}^\#}(a_{x,\mathfrak{q}}) \right)_u \end{aligned}$$

where with the notation  $\mathfrak{q}|u$  we denote all ideals  $\mathfrak{q} \in \text{Spec}^1 \mathcal{O}_x$  sitting over  $u$ .

**Lemma 5.9.** *Let  $f \in \mathbf{A}'_{X,x}$  such that  $\text{Tr}_x(fg) \in (K'_x)^\#$  for any  $g \in K'_x$ , then  $f \in K'_x$ .*

*Proof.* See [12, Lemma 3.4].  $\square$

**Theorem 5.10.**  $A_{\widehat{02}}^\perp = A_{\widehat{02}}$ .

*Proof.* First of all let's prove that  $A_{\widehat{02}} \subseteq A_{\widehat{02}}^\perp$ . We have to show that for any  $\alpha, \beta \in A_{\widehat{02}}$ ,  $d_\omega(\alpha, \beta) = \xi^\omega(\alpha\beta) = 1$ . Let  $a = \alpha\beta$ , then

$$\begin{aligned} \xi^\omega(a) &= \prod_{\substack{x \in \bar{y}, \\ \bar{y} \subset \bar{X}}} \text{Cres}_{x,\bar{y}}(\omega a_{x,\bar{y}}) \prod_{\substack{p \in X_\sigma, \\ \sigma \in B_\infty}} \text{Cres}_{p,\sigma}(\omega a_{p,\sigma}) = \\ &= \prod_{\substack{x \in X, \\ \bar{y} \ni x}} \text{Cres}_{x,\bar{y}}(\omega a_{x,\bar{y}}) \prod_{\substack{p \in X_{\bar{K},\sigma}, \\ \bar{y} \ni p, \\ \sigma \in B_\infty}} \text{Cres}_{p,\sigma}(\omega a_{p,\sigma}) \text{Cres}_{p,\bar{y}}(\omega a_{p,\bar{y}}) \prod_{\substack{p \in X_\sigma \setminus X_{\bar{K},\sigma}, \\ \sigma \in B_\infty}} \text{Cres}_{p,\sigma}(\omega a_{p,\sigma}). \end{aligned}$$

We can conclude  $\xi^\omega(a) = 1$  thanks to Proposition 3.6(1) and from the explicit definition of  $A_{\widehat{02}}$  at infinity.

Now we show the inclusion  $A_{\widehat{02}}^\perp \subseteq A_{\widehat{02}}$ . Fix  $a = (a_{x,\bar{y}}) \times (a_{p,\sigma}) \in A_{\widehat{02}}^\perp$  and assume  $\omega = f dt$ , we consider 3 cases:

$x = p$  is an algebraic point on  $X_\sigma$ . For any  $g \in K_\sigma((t))$  we consider the element  $(f^{-1}g, f^{-1}g) \in \Delta_{p,\sigma}$ , then if  $\bar{y}$  is the unique horizontal curve containing  $p$  we obtain

$$\text{Cres}_{p,\bar{y}}(a_{p,\bar{y}}f^{-1}g\omega) \cdot \text{Cres}_{p,\sigma}(a_{p,\sigma}f^{-1}g\omega) = 1.$$

This means

$$\text{res}_{p,\bar{y}}(a_{p,\bar{y}}gdt) - \text{res}_{p,\sigma}(a_{p,\sigma}gdt) \in \ker \psi_\sigma = \frac{1}{2}\mathbb{Z} + \mathbb{R}i. \quad (16)$$

Since equation (16) holds for any  $g \in K_\sigma((t))$ , it is clear that it must be  $(a_{p,\bar{y}}, a_{p,\sigma}) \in \Delta_{p,\sigma}$ .

$x = p$  is a transcendental point on  $X_\sigma$ . It follows easily from the fact that polynomials over  $K$  do not have zeros in points transcendental over  $K$ .

$x$  is a point on  $X$ . Recall that  $\mathcal{O}_x$  is a finite ring extension of  $\mathcal{O}_b[[t]]$ .

We first treat the case where there are transcendental curves passing by  $x$ ; let's extend the element  $(a_{x,\bar{y}})_{\bar{y} \ni x}$  to an element  $(a'_{x,q})_q \in \mathbf{A}'_{X,x}$  in the following way: for a transcendental curve  $q \in \mathfrak{T}(x)$  let's insert  $a'_{x,q} \in K_x$ ; at all other primes nothing changes. Now let  $g \in K_x$ , then:

$$\prod_{q \in \text{Spec}^1 \mathcal{O}_x} \text{Cres}_{x,q}(a'_{x,q}g\omega) = \underbrace{\prod_{\bar{y} \ni x} \text{Cres}_{x,\bar{y}}(a_{x,\bar{y}}g\omega)}_{(i)} \underbrace{\prod_{q \in \mathfrak{T}(x)} \text{Cres}_{x,q}(a'_{x,q}g\omega)}_{(ii)} = 1 \quad (17)$$

where (i) = 1 because  $(a_{x,\bar{y}}) \times (a_{p,\sigma}) \in A_{02}^\perp$  and (ii) = 1 thanks to Lemma 5.3. Since  $K_x$  is sequentially dense in  $K'_x$ , equation (17) implies that for any  $h \in K'_x$

$$\prod_{q \in \text{Spec}^1 \mathcal{O}_x} \text{Cres}_{x,q}(a'_{x,q}h\omega) = 1. \quad (18)$$

Now we use equation (18) and the functoriality of the residue with respect to the trace map:

$$\begin{aligned} \mathcal{O}_b \ni \sum_q \text{res}_{x,q}(a'_{x,q}h\omega) &= \sum_u \sum_{q|u} \text{res}_{x,u}^\# \left( \text{Tr}_{K_{x,q}|K_{x,u}^\#} (a'_{x,q}h\omega) \right) = \\ &= \sum_u \text{res}_{x,u}^\# \left( \sum_{q|u} \text{Tr}_{K_{x,q}|K_{x,u}^\#} (a'_{x,q}h\omega) \right) = \sum_u \text{res}_{x,u}^\# \left( \sum_{q|u} \text{Tr}_{K_{x,q}|K_{x,u}^\#} (a'_{x,q})h\omega \right). \end{aligned}$$

By Lemma 5.8 we can conclude that  $\text{Tr}_x (a'_{x,q})_q \in (K'_x)^\#$  diagonally. By replacing  $a_{x,\bar{y}}$  with  $ca'_{x,\bar{y}}$  for any  $c \in K'_x$  we can again conclude that  $\text{Tr}_x (ca'_{x,q})_q \in (K'_x)^\#$  diagonally. At this point we can use Lemma 5.9 to conclude that  $(a'_{x,q})_q \in K'_x$ . It means that  $(a_{x,\bar{y}})_{\bar{y} \ni x} \in K_x$  by the choice of  $(a'_{x,q})_q$ .

If there are no transcendental curves passing by  $x$ , then  $\mathbf{A}'_{X,x} = \mathbf{A}_{X,x}$  and  $K_x = K'_x$  by corollary 5.5. Then we can apply a simplified version of the argument used above to conclude the proof.  $\square$

*Remark 5.11.* We were informed by I. Fesenko that there is an alternative proof of Theorem 5.10 which uses an arithmetic version of his argument in [10].

## 6 Idelic interpretation of Arakelov intersection theory

A prerequisite for this section is the whole appendix B. We need to work with complex fibres at infinity, therefore in this section we put by simplicity of notations  $X_\sigma = X \times_\sigma \text{Spec } \mathbb{C}$  like one usually does in Arakelov geometry. In [8], it is described how to get a lift of the Deligne pairing (i.e. the schematic part of the Arakelov intersection number) at the level of ideles. Let's summarise the result: first of all we

consider the idelic complex attached to the (uncompleted) surface  $X$

$$\begin{aligned} \mathcal{A}_X^\times : \quad A_0^\times \oplus A_1^\times \oplus A_2^\times &\xrightarrow{d_x^0} A_{01}^\times \oplus A_{02}^\times \oplus A_{12}^\times \xrightarrow{d_x^1} A_{012}^\times \\ (a_0, a_1, a_2) &\longmapsto (a_0 a_1^{-1}, a_2 a_0^{-1}, a_1 a_2^{-1}) \\ (a_{01}, a_{02}, a_{12}) &\longmapsto a_{01} a_{02} a_{12} \end{aligned} \quad (19)$$

and we note that we have a surjective map:

$$\begin{aligned} p : \ker(d_x^1) &\rightarrow \text{Div}(X) \\ (\alpha, \beta, \alpha^{-1} \beta^{-1}) &\mapsto \sum_{y \subset X} v_y(\alpha_{x,y}) [y]. \end{aligned}$$

Then by globalising the Kato's symbol, we define an idelic Deligne pairing  $\langle \cdot, \cdot \rangle_i : \ker(d_x^1) \times \ker(d_x^1) \rightarrow \text{Pic}(B)$  which descends to the Deligne pairing  $\langle \cdot, \cdot \rangle : \text{Pic}(X) \times \text{Pic}(X) \rightarrow \text{Pic}(B)$ . In turn, the Deligne pairing is strictly related to intersection theory because for any two divisors  $D, E \in \text{Div}(X)$ , the class in  $\text{Pic}(B)$  of the divisor

$$\langle D, E \rangle = \varphi_* i(D, E) = \sum_{x \in X} [k(x) : k(\varphi(x))] i_x(D, E) [\varphi(x)]$$

is equal to  $\langle \mathcal{O}_X(D), \mathcal{O}_X(E) \rangle$ . Note that we have used the brackets  $\langle \cdot, \cdot \rangle$  to denote two different (but strictly related) objects, but the clash of notations shouldn't confuse the reader.

The contribution at infinity to the Arakelov intersection pairing is given by the  $*$ -product between Green functions, so the next step in our theory is to find an idelic description of it. We need to work with an enlargement of  $\mathbf{A}_{\widehat{X}}$ , namely  $\mathbf{A}_{\widehat{X}}^{\mathbb{C}} := \mathbf{A}_X \oplus \prod_{\sigma \in B_\sigma} (\mathbf{A}_{X_\sigma} \oplus \mathbf{A}_{X_\sigma})$ . We want to find a surjective map:

$$(\mathbf{A}_{X_\sigma}^\times \oplus \mathbf{A}_{X_\sigma}^\times) \supseteq S \rightarrow \mathbb{Z}G(X_\sigma)$$

where  $S$  is an adequate subset of  $\mathbf{A}_{X_\sigma}^\times \oplus \mathbf{A}_{X_\sigma}^\times$  still to be determined and  $\mathbb{Z}G(X_\sigma)$  is the vector space of Green functions on  $X_\sigma$  with integer orders.

*Remark 6.1.* First of all let's introduce a notation. For any  $a = (a_x) \in \mathbf{A}_{X_\sigma}$ , with  $a(x)$  we denote the projection of  $a_x$  onto the residue field  $\mathbb{C}$  (when it is well defined).

Let  $\mathcal{F}(X_\sigma, \mathbb{R}_\infty)$  be the set of functions  $f : X_\sigma \rightarrow \mathbb{R} \cup \{\pm\infty\}$ , then we have the following map:

$$\begin{aligned} \Theta : \mathbf{A}_{X_\sigma}^\times \times \mathbf{A}_{X_\sigma}^\times &\rightarrow \mathcal{F}(X_\sigma, \mathbb{R}_\infty) \\ (a, b) &\mapsto -|b| \log(a\bar{a}) := [x \mapsto -|b(x)| \log(a(x)\overline{a(x)})] \end{aligned}$$

where  $\overline{a(x)}$  denotes the complex conjugate and  $|\cdot|$  is the usual complex absolute value. Note that  $\mathbb{Z}G(X_\sigma) \subset \mathcal{F}(X_\sigma, \mathbb{R}_\infty)$ , then put

$$G(\mathbf{A}_{X_\sigma}^\times) := \{(a, b) \in \Theta^{-1}(\mathbb{Z}G(X_\sigma)) : v_x(a_x) = \text{ord}_x^G(\Theta(a, b)), \forall x \in X_\sigma\}.$$

We get the map:

$$\pi_\sigma := \Theta|_{G(\mathbf{A}_{X_\sigma}^\times)} : G(\mathbf{A}_{X_\sigma}^\times) \rightarrow \mathbb{Z}G(X_\sigma).$$

**Proposition 6.2.** *The map  $\pi_\sigma$  is surjective.*

*Proof.* Let  $g \in \mathbb{Z}G(X_\sigma)$ , by Proposition B.6, there exist a  $C^\infty$  hermitian invertible sheaf  $(\mathcal{L}, h)$  on  $X$  and a meromorphic section  $s = \{(s_j, U_j)\}$  of  $\mathcal{L}$  such that we can write:

$$g = -\log h(s, s).$$

We can choose  $a \in \mathbf{A}_{X_\sigma}^\times$  such that  $a(x) = s(x)$  (when  $s(x)$  is well defined) and  $v_x(a_x) = \text{ord}_x(s)$  for any  $x \in X_\sigma$ . Now we can write

$$g(x) = -\log h_x(a(x), a(x)).$$

Since  $z \mapsto h_x(z, z)$  is the square of a complex absolute value, we have  $\log h_x(a(x), a(x)) = 2s_x \log(a(x)\overline{a(x)})$  with  $s_x \in \mathbb{R}_{>0}$ . Let's choose  $b = (b_x) \in \mathbf{A}_{X_\sigma}^\times$  such that  $|b(x)| = \frac{s_x}{2}$ , then

$$g(x) = -|b(x)| \log\left(a(x)\overline{a(x)}\right).$$

The fact that  $v_x(a_x) = \text{ord}_x^G(g)$  follows directly from the fact that for any hermitian metric  $h$  and meromorphic section  $s$  we have the equality:

$$\text{div}^G(-\log(h(s, s))) = \text{div}(s).$$

(See Proposition B.3). □

So far, we have the idelic description of Green functions with integer orders thanks to the projection  $\pi_\sigma$ . Now let's fix a (normalised) Kähler fundamental form  $\Omega_\sigma$  on  $X_\sigma$  and consider  $G_0^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times) := \pi_\sigma^{-1}(\mathbb{Z}G_0^{\Omega_\sigma}(X_\sigma))$ ,  $G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times) := \pi_\sigma^{-1}(\mathbb{Z}G^{\Omega_\sigma}(X_\sigma))$ . For pairs  $(\alpha, \beta) \in G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times) \times G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times)$  such that  $\text{div}^G(\pi_\sigma(\alpha))$  and  $\text{div}^G(\pi_\sigma(\beta))$  have no common components we want to find a product  $\alpha *_i \beta$  such that the following equality holds:

$$\begin{array}{ccc} (\alpha, \beta) & & \\ \downarrow & \searrow & \\ (\pi_\sigma(\alpha), \pi_\sigma(\beta)) & \longmapsto & \alpha *_i \beta = \pi_\sigma(\alpha) * \pi_\sigma(\beta) \end{array}$$

As a consequence of the symmetry of the  $*$ -product we will get also the symmetry of  $*_i$ . For any  $\alpha = (a, b) \in G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times)$  let's put:

$$\xi(\alpha) := e^{\int_{X_\sigma} \log(ba\bar{a})\Omega_\sigma}$$

**Definition 6.3.** Let  $\alpha = (a, b), \beta = (c, d) \in G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times)$ , then the idelic  $*$ -product is defined as:

$$\alpha *_i \beta := - \sum_{x \in X_\sigma} v_x(c_x) |b(x)| \log\left(a(x)\overline{a(x)} \xi(\alpha)^{\frac{1}{|b(x)|}}\right) + \log(\xi(\alpha)) \text{ideg}(c) + \log(\xi(\beta)) \text{ideg}(a).$$

where  $\text{ideg}$  is the idelic degree map defined as:

$$\begin{aligned} \text{ideg} : \mathbf{A}_{X_\sigma}^\times &\rightarrow \mathbb{Z} \\ (\alpha_x)_x &\mapsto \sum_{x \in X_\sigma} v_x(\alpha_x). \end{aligned}$$

**Proposition 6.4.**  $(\alpha, \beta) \in G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times) \times G^{\Omega_\sigma}(\mathbf{A}_{X_\sigma}^\times)$  such that  $\text{div}^G(\pi_\sigma(\alpha))$  and  $\text{div}^G(\pi_\sigma(\beta))$  have no common component; then  $\alpha *_i \beta = \pi_\sigma(\alpha) * \pi_\sigma(\beta)$ .

*Proof.* Put  $g_1 = \pi_\sigma(\alpha)$  and  $g_2 = \pi_\sigma(\beta)$ , then by Proposition B.8 we can write  $g_1 = g_{1,0} + c_1$  and  $g_2 = g_{2,0} + c_2$  for,  $g_{1,0}, g_{2,0} \in G_0^{\Omega_\sigma}(X_\sigma)$ ,  $c_1 = \log(\xi(\alpha))$  and  $c_2 = \log(\xi(\beta))$ . An easy calculation shows that:

$$g_1 * g_2 = \sum_{x \in X_\sigma} \text{ord}_x^G(g_{2,0}) g_{1,0}(x) + c_1 \sum_{x \in X_\sigma} \text{ord}_x^G(g_{2,0}) + c_2 \sum_{x \in X_\sigma} \text{ord}_x^G(g_{1,0}).$$

Then it is enough to note the following equalities:

$$\begin{aligned} \text{ord}_x^G(g_{1,0}) &= \text{ord}_x^G(g_1) = v_x(a_x), \\ \text{ord}_x^G(g_{2,0}) &= \text{ord}_x^G(g_2) = v_x(c_x), \\ g_{1,0}(x) &= g_1(x) - \log(\xi(\alpha)) = -|b(x)| \log(a(x)\overline{a(x)}) - \log(\xi(\alpha)). \end{aligned}$$

□

Let's write an element  $\alpha \in \mathbf{A}_X^\times \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_\sigma}^\times \oplus \mathbf{A}_{X_\sigma}^\times)$  in the following way:

$$\alpha = \alpha_X \times (\alpha_\sigma)_\sigma$$

with  $\alpha_X \in \mathbf{A}_X^\times$  and  $\alpha_\sigma \in \mathbf{A}_{X_\sigma}^\times \oplus \mathbf{A}_{X_\sigma}^\times$ , then we have a surjective map:

$$\begin{aligned} \widehat{p} : \ker(d_X^1) \oplus \prod_{\sigma} G(\mathbf{A}_{X_{\sigma}}^{\times}) &\rightarrow \operatorname{Div}(X) \oplus \bigoplus_{\sigma} G(X_{\sigma}) \\ \alpha = \alpha_X \times (\alpha_{\sigma})_{\sigma} &\mapsto \left( p(\alpha_X), \sum_{\sigma} \pi_{\sigma}(\alpha_{\sigma}) X_{\sigma} \right) \end{aligned}$$

where  $p : \ker(d_X^1) \rightarrow \operatorname{Div}(X)$  is the usual projection on usual divisors and  $\pi_{\sigma} : G(\mathbf{A}_{X_{\sigma}}^{\times}) \rightarrow G(X_{\sigma})$  is the projection on Green functions.

**Definition 6.5.** Let's put

$$\operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times}) := \widehat{p}^{-1}(\operatorname{Div}_{\operatorname{Ar}}(X, \Omega)),$$

and let  $\alpha, \beta \in \operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times})$  such that  $(\widehat{p}(\alpha), \widehat{p}(\beta)) \in \Upsilon_{\operatorname{Ar}}$  then the *idelic Arakelov intersection pairing* is given by:

$$\alpha.\beta := \deg(\langle \alpha_X, \beta_X \rangle_i) + \frac{1}{2} \sum_{\sigma} \varepsilon_{\sigma} \alpha_{\sigma} *_i \beta_{\sigma}$$

where  $\deg$  is the usual degree of line bundles,  $\langle \cdot, \cdot \rangle_i$  is the idelic Deligne pairing and  $\alpha_{\sigma} *_i \beta_{\sigma}$  is the idelic  $*$ -product.

We have to check that definition 6.5 gives the correct extension of the Arakelov pairing.

**Theorem 6.6.** Let  $\alpha, \beta \in \operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times})$  such that  $\widehat{p}(\alpha) = \widehat{D}$  and  $\widehat{p}(\beta) = \widehat{E}$ , with  $(\widehat{D}, \widehat{E}) \in \Upsilon_{\operatorname{Ar}}$ , then  $\alpha.\beta = \widehat{D}.\widehat{E}$ . In other words the idelic Arakelov intersection pairing extends to a pairing:

$$\operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times}) \times \operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times}) \rightarrow \mathbb{R}$$

and the following diagram is commutative:

$$\begin{array}{ccc} \operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times}) \times \operatorname{Div}(\mathbf{A}_{\widehat{X}}^{\times}) & & \\ \downarrow \widehat{p} \times \widehat{p} & \searrow & \\ \operatorname{Div}_{\operatorname{Ar}}(X) \times \operatorname{Div}_{\operatorname{Ar}}(X) & \longrightarrow & \mathbb{R} \end{array}$$

*Proof.* It follows easily from the definitions. □

## Appendices

### A Semi-topological algebraic structures

#### A.1 Basic notions

**Definition A.1.** A topological abelian group  $(G, \tau)$  is *linearly topologised* (or has a *linear topology*) if there is a local basis at 0 made of subgroups. A morphism between linearly topologised groups is a continuous homomorphism. The category of linearly topologised group is denoted by **LTA**.

**Proposition A.2.** Let  $G$  be an abelian group and fix a non-empty collection of subgroups  $\mathcal{F} = \{U_i\}_{i \in I}$ . If  $G$  is endowed with the topology  $\tau$  generated by  $\{x + U_i\}_{i \in I, x \in G}$ , then it becomes a linearly topologised group.

*Proof.* First we show that  $G$  is a topological group: we want the inversion  $\iota : G \rightarrow G$  and the sum  $\sigma : G \times G \rightarrow G$  to be continuous. We check this for the subbase  $\{x + U_i\}_{i \in I, x \in G}$ . Obviously  $\iota^{-1}(U_i + x) = U_i - x \in \tau$ . Then we prove that the following equality holds:

$$\sigma^{-1}(U_i + x) = \bigcup_{y \in G} (U_i + y) \times (U_i + x - y).$$

The inclusion  $\supseteq$  is evident, so let  $(z, z') \in \sigma^{-1}(U_i + x)$ , then  $z = u + (x - z')$  for  $u \in U_i$ . If we write  $z' = 0 + x - (x - z')$  and we put  $y = x - z'$  we finally get  $(z, z') = (u + y, 0 + x - y) \in (U_i + y) \times (U_i + x - y)$ . For the last statement consider the family

$$\mathcal{B} := \{U \in \tau : U \text{ is finite intersection of elements of } \mathcal{F}\}.$$

Then  $\mathcal{B}$  is a local basis at 0 made of subgroups. □

**Definition A.3.** The linear topology on an abelian group  $G$  obtained from a family of subgroups  $\{U_i\}_{i \in I}$ , as it is described in Proposition A.2, is called *the linear topology generated by  $\{U_i\}_{i \in I}$* .

In this setting, concepts like initial and final topologies are well defined. Let  $G$  be an abelian group and consider some homomorphisms of groups  $\{\varphi_\alpha : G \rightarrow H_\alpha\}_\alpha$  and  $\{\psi_\beta : H_\beta \rightarrow G\}_\beta$ , where the  $H_\alpha$  and  $H_\beta$  are all linearly topologised. The *initial linear topology* on  $G$  with respect to  $\{\varphi_\alpha\}_\alpha$  is the linear topology generated by

$$\{\varphi_\alpha^{-1}(V_\alpha) : V_\alpha \subseteq H_\alpha \text{ is an open subgroup}\}_\alpha.$$

This is the coarsest linear topology which makes all the  $\varphi_\alpha$  continuous. The *final linear topology* on  $G$  with respect to  $\{\psi_\beta\}_\beta$  is the linear topology generated by

$$\left\{U \subseteq G : U \text{ is a subgroup and } \psi_\beta^{-1}(U) \text{ is open for any } \beta\right\}.$$

This is the finest linear topology which makes all the  $\psi_\beta$  continuous.

**Proposition A.4.** **LTAb** is an additive category and moreover it admits inverse and direct limits.

*Proof.* The nontrivial statements are those involving the categorical limits. In particular  $\varprojlim_i G_i$  and  $\varinjlim_j G_j$  are the usual limits in the category of groups, endowed respectively with the initial and final linear topology.

*Remark A.5.* By commodity, in the category of linearly topologised groups, we call the limits  $\varprojlim_i G_i$  and  $\varinjlim_j G_j$  respectively *linear inverse limit* and *linear direct limit*.

**Definition A.6.** A *ST ring* (ST stands for semi-topological) is a ring  $A$  endowed with a topology satisfying the following two properties:

- $(A, +)$  is a linearly topologised abelian group.
- For any  $a \in A$  the map  $\lambda_a : A \rightarrow A$ , such that  $\lambda_a(x) = ax$ , is continuous.

A morphism of ST rings is a continuous homomorphisms of rings. The category of ST rings is denoted as **STRing**. Moreover  $B$  is a ST  $A$ -algebra if there is a morphism of ST rings  $\varphi : A \rightarrow B$ . The category of ST  $A$ -algebras is **A-STAlg**.

**Proposition A.7.** **STRing** and **A-STAlg** admit inverse and direct limits.

*Proof.* We show it only for rings. Let  $A = \varprojlim_i A_i$  be the usual inverse limit in the category of rings and topologise its additive structure by taking the linear inverse limit topology. Thus we have the coarsest linear topology on  $(A, +)$  such that the projections  $\pi_j : A \rightarrow A_j$  are continuous. Assume that  $\Lambda_{(a_i)}$  is the multiplication by  $(\dots, a_i, a_{i+1}, \dots)$  in  $A$  and consider the composition:  $A \xrightarrow{\Lambda_{(a_i)}} A \xrightarrow{\pi_j} A_j$ , given by

$$x = (\dots x_i, x_{i+1}, \dots) \mapsto (\dots a_i x_i, a_{i+1} x_{i+1}, \dots) \mapsto a_j x_j.$$

Since  $\pi_j \circ \Lambda_{(a_i)}(x) = \lambda_{a_j} \circ \pi_j(x)$ , we can conclude that  $\pi_j \circ \Lambda_{(a_i)}$  is continuous. Finally if  $\pi_j^{-1}(V_j) \subset A$  is an element in the subbase of  $A$ , then  $\Lambda_{(a_i)}^{-1}(\pi_j^{-1}(V_j))$  is open in  $A$ .

Let  $A = \varinjlim_i A_i$  be the usual direct limit in the category of rings and topologise its additive structure by taking the linear direct limit topology. Thus we have the finest linear topology on  $(A, +)$  such that the maps  $\phi_i : A_i \rightarrow A$  are continuous. Let's denote with  $\mu_{ij} : A_i \rightarrow A_j$  the continuous homomorphisms in the directed set  $\{A_i\}_i$ ; moreover  $\Lambda_{[(j,a)]}$  is the multiplication in  $A = (\sqcup_i A_i) / \sim$  for the fixed element  $[(j, a)]$  where  $a \in A_j$ . Note that the composition:  $A_i \xrightarrow{\phi_i} A \xrightarrow{\Lambda_{[(j,a)]}} A$ , given by

$$x \mapsto [(i, x)] \mapsto [k, \mu_{jk}(a)\mu_{ik}(x)].$$

is continuous. Thus if  $U \subset A$  is open, then  $\phi_1^{-1}\left(\Lambda_{[(j,a)]}^{-1}(U)\right)$  is open and by definition of final linear topology we can conclude that  $\Lambda_{[(j,a)]}^{-1}(U)$  is open in  $A$ . □

**Definition A.8.** Let  $A$  be a ST ring. A *ST  $A$ -module* is an  $A$ -module satisfying the following properties:

- $M$  is a linearly topologised abelian group.
- For any  $a \in A$  and any  $m \in M$  the maps  $\lambda_a^M : M \rightarrow M$  and  $\rho_m : A \rightarrow M$  such that  $\lambda_a(x) = ax$  and  $\rho_m(x) = xm$  are continuous.

A morphism of ST modules is a continuous homomorphism of  $A$ -modules. If  $A$  is a ST field then  $M$  is called a *ST vector space*.

**Proposition A.9.** Let  $A$  be a ST ring, and  $M$  an  $A$ -module. If  $M$  is endowed with the final linear topology with respect to the group homomorphisms  $\rho_m : A \rightarrow M$ , then  $M$  is a ST  $A$ -module

*Proof.* See [25, pag. 17]. □

**Definition A.10.** The topology on  $M$  described in Proposition A.9 is called the *fine  $A$ -module topology*.

## A.2 Ind/pro topologies

Now we present the crucial part of this very general theory. Given a ST ring  $A$ , we describe two procedures called (C) and (L) that give canonical topologies of ST rings respectively on  $\varprojlim_r A/\mathfrak{p}^r$  and  $A_{\mathfrak{p}}$  for any prime ideal  $\mathfrak{p} \subset A$ . We need the following lemma:

**Lemma A.11.** Let  $\varphi : A \rightarrow B$  be a ring homomorphism where  $A$  is a ST ring. Consider  $B$  as an  $A$ -module endowed with the fine  $A$ -module topology, then  $B$  is a ST ring.

*Proof.* [25, Proposition 1.2.9.(b)]. □

(C) For any  $r > 0$  we put on  $A/\mathfrak{p}^r$  the fine  $A$ -module topology, so by Lemma A.11  $A/\mathfrak{p}^r$  is a ST ring. By Proposition A.7 we can endow  $\varprojlim_r A/\mathfrak{p}^r$  with a structure of ST ring.

(L)  $A_{\mathfrak{p}}$  is naturally an  $A$ -module, so we endow it with the fine  $A$ -module topology. Again by Lemma A.11 we conclude that  $A_{\mathfrak{p}}$  is a ST ring.

Let  $R$  be a ST ring ring and put on  $A = R[t]$  the fine  $R$ -module topology. Consider the ring of formal Laurent power series  $R((t))$ , then as linear projective limit we have:

$$R[[t]] = \varprojlim_r \frac{R[t]}{t^r R[t]}.$$

Therefore we consider on  $R((t))$  the topology induced in the following way:

$$A = R[t] \xrightarrow{(C)} R[[t]] \xrightarrow{(L)} R((t)). \quad (20)$$

This is called the ind/pro-topology. We have an isomorphism of ST  $R$ -modules

$$R((t)) \cong \left( \bigoplus_{n \in \mathbb{N}} R \right) \oplus \prod_{n \in \mathbb{N}} R$$

and each subgroup of the form  $t^r R[[t]]$ , for  $r \in \mathbb{Z}$ , is closed in  $R((t))$ . Let  $\xi \in \widehat{R((t))}$  be a nontrivial character. The *conductor* of  $\xi$  is

$$c_{\xi} := \min \left\{ i \in \mathbb{Z} : \xi \in (t^i R[[t]])^{\perp} \right\}.$$

*Remark A.12.* If  $R$  is any topological field endowed with a topology which is not necessarily linear, it is anyway possible to use (C) and (L) to give a topology on  $R((t))$ . First of all one puts on  $R[t]$  the final topology with respect to the maps  $R \rightarrow R[t]$  given by  $r \mapsto rp(t)$  for any  $p(t) \in R[t]$ . At this point it is enough to use the procedures (C) and (L) in the category of topological abelian groups. Note that if  $R$  is a discrete field, then the ind/pro-topology on  $R((t))$  is the usual discrete valuation topology on the field of Laurent series.

## B Arakelov geometry

This section is just a collection of basic results about Arakelov geometry for arithmetic surfaces, way more details about Arakelov geometry can be found for example in [15]. We will maintain the same notations used so far for the arithmetic surface  $\varphi : X \rightarrow B$ , but in this section  $X_\sigma = X \times_\sigma \text{Spec } \mathbb{C}$ . Moreover we assume the reader to be familiar with complex analytic geometry for Riemann surfaces.

### B.1 Green functions and \*-product

Let's fix a connected Riemann surface  $C$ .

**Definition B.1.** A *Green function* on  $C$  is a map  $g : U \subseteq C \rightarrow \mathbb{R}$  satisfying the following properties:

- (1)  $U = C \setminus \{x_1, \dots, x_r\}$  for  $r \in \mathbb{N}$ .
- (2)  $g$  is a  $C^\infty$  function on  $U$ .
- (3) For any point  $x \in \{x_1, \dots, x_r\}$  there exist a real number  $a \in \mathbb{R}$  and a  $C^\infty$  function  $u$  on an open neighborhood of  $x$  such that the equality:

$$g = a \log |z|^2 + u$$

holds in an open neighborhood of  $x$  contained in a holomorphic chart  $(V, z)$  centred in  $x$ .

The number  $a \in \mathbb{R}$  arising in condition (3) of definition B.1 depends only on the point  $x$  and it is uniquely defined.

**Definition B.2.** Let  $g$  be a Green function on  $C$  such that around a point  $x \in C$  it can be written as  $g = a \log |z|^2 + u$ . Then we put  $\text{ord}_x^G(g) := -a$  and we call it *the Green order of  $g$  at  $x$* . If  $x$  is a point in the domain of  $g$ , then  $\text{ord}_x^G(g) := 0$ .

Clearly  $\text{ord}_x^G(g) \neq 0$  only at a finite number of points. The Green functions on  $C$  form a real vector space  $G(C)$ , and for any  $g, g' \in G(C)$

$$\begin{aligned} \text{ord}_x^G(\lambda g) &= \lambda \text{ord}_x^G(g) \quad \text{for any } \lambda \in \mathbb{R}, \\ \text{ord}_x^G(g + g') &= \text{ord}_x^G(g) + \text{ord}_x^G(g'). \end{aligned}$$

Let's denote with  $\text{Div}(C)_\mathbb{R} := \text{Div}(C) \otimes_{\mathbb{Z}} \mathbb{R}$  the vector space of  $\mathbb{R}$ -divisors on  $C$ , then we have a  $\mathbb{R}$ -linear map:

$$\begin{aligned} \text{div}^G : G(C) &\rightarrow \text{Div}(C)_\mathbb{R} \\ g &\mapsto \sum_{x \in C} \text{ord}_x^G(g)[x] \end{aligned}$$

For any Green function  $g \in G(C)$  and any  $\mathbb{R}$ -divisor  $D = \sum_x \lambda_x [x]$ , we put  $\tilde{g}(D) := \sum_x \lambda_x g(x)$  when the values  $g(x)$  are well defined.

**Proposition B.3.** Let  $(\mathcal{L}, h)$  be a  $C^\infty$  hermitian invertible sheaf on  $C$ , and let  $s$  be a nonzero meromorphic section of  $\mathcal{L}$ , then the map  $-\log(h(s, s))$  is a Green function on  $C$  such that  $\text{div}^G(-\log(h(s, s))) = \text{div}(s)$ .

*Proof.* See [15, lemma 4.8]. □

The following result is an immediate consequence of Proposition B.3:

**Proposition B.4.** The map  $\text{div}^G : G(C) \rightarrow \text{Div}(C)_\mathbb{R}$  is surjective.

Let's define a very important subspace of  $\mathbb{Z}G(C)$ :

**Definition B.5.** The vector space of Green functions with integer orders on  $C$  is:

$$\mathbb{Z}G(C) := \left\{ g \in G(C) : \text{ord}_x^G(g) \in \mathbb{Z} \ \forall x \in C \right\}$$

The next result shows that any Green function which induces a divisor on  $C$  is actually of the form  $-\log(h(s, s))$  for some meromorphic section  $s$  of a  $C^\infty$  hermitian invertible sheaf  $(\mathcal{L}, h)$ .

**Proposition B.6.** *Let  $g \in \mathbb{Z}G(C)$ , then there exist a  $C^\infty$  hermitian invertible sheaf  $(\mathcal{L}, h)$  on  $C$  and a meromorphic section  $s$  of  $\mathcal{L}$  such that  $g = -\log(h(s, s))$ .*

*Proof.* See again [15, lemma 4.8]. □

From now on, in this subsection we fix a Kähler fundamental form  $\Omega$  on  $C$  such that  $\int_C \Omega = 1$ . Let's define some subsets of  $G(C)$ :

$$G^\Omega(C) := \{g \in G(C) : \Delta_{\bar{\partial}}(g) \text{ is constant}\},$$

$$G_0^\Omega(C) := \{g \in G^\Omega(C) : \int_C g\Omega = 0\},$$

$$\mathbb{Z}G^\Omega(C) := \mathbb{Z}G(C) \cap G^\Omega(C),$$

$$\mathbb{Z}G_0^\Omega(C) := \mathbb{Z}G(C) \cap G_0^\Omega(C).$$

**Theorem B.7.** *The map  $\text{div}^G|_{G_0^\Omega(C)} : G_0^\Omega(C) \rightarrow \text{Div}(C)_\mathbb{R}$  is an isomorphism.*

*Proof.* See [15, Theorem 4.10]. □

**Proposition B.8.** *For any  $g \in G^\Omega(C)$  there exists a unique decomposition  $g = g_0 + c$  for  $g_0 \in G_0^\Omega(C)$  and  $c \in \mathbb{R}$ .*

*Proof.* See again [15, Theorem 4.10]. □

**Definition B.9.** The inverse map of  $\text{div}^G|_{G_0^\Omega(X)}$  is denoted as:

$$\begin{aligned} \mathcal{G}^\Omega : \text{Div}(X)_\mathbb{R} &\rightarrow G_0^\Omega(X) \\ D &\mapsto \mathcal{G}^\Omega(D) \end{aligned}$$

and we can define the following function:

$$\begin{aligned} g^\Omega : (X \times X) \setminus \Delta_{X \times X} &\rightarrow \mathbb{R} \\ (p, q) &\mapsto g^\Omega(p, q) := \mathcal{G}^\Omega([p])(q) \end{aligned}$$

where  $\Delta_{X \times X}$  denotes the diagonal subset of  $X \times X$ .

By construction  $g^\Omega$  is  $C^\infty$  in the variable  $q$ , but, as we will see soon (corollary B.14),  $g^\Omega$  turns out to be symmetric, therefore it is  $C^\infty$ . Since  $g^\Omega(p, \cdot) \in G_0^\Omega(X) \subset G^\Omega(X)$ , then  $dd^c(g^\Omega(p, \cdot)) = \alpha\Omega$  for a constant  $\alpha \in \mathbb{C}$ , but

$$1 = \deg^G(g^\Omega(p, \cdot)) = \int_X dd^c(g^\Omega(p, \cdot)) = \int_X \alpha\Omega = \alpha.$$

Hence  $\alpha = 1$  and

$$dd^c(g^\Omega(p, \cdot)) = \Omega. \tag{21}$$

Thus, amongst all Green functions, those of the form  $g^\Omega(p, \cdot)$  satisfy the Poisson differential equation (21). this feature will be very useful for intersection theory.

Another important property is that for any fixed  $p \in X$ :

$$\int_X g^\Omega(p, \cdot)\Omega = \int_X \mathcal{G}^\Omega([p])\Omega = 0 \tag{22}$$

because  $\mathcal{G}^\Omega([p]) \in G_0^\Omega(X)$ .

*Remark B.10.*  $g^\Omega$  can be defined as the *unique* function on  $(X \times X) \setminus \Delta_{X \times X}$  with values in  $\mathbb{R}$  satisfying the following properties:

- (1) Around any point  $p \in X$  we can write  $g^\Omega(p, \cdot) = -\log|z|^2 + u$ , where  $z$  is a chart centred in  $p$  and  $u$  is  $C^\infty$ .
- (2)  $dd^c(g^\Omega(p, \cdot)) = \Omega$ .
- (3)  $\int_X g^\Omega(p, \cdot)\Omega = 0$ .

This is how Arakelov defined  $g^\Omega$  in [2] and [1]. In the literature  $g^\Omega$  is usually called *the Green function of  $X$  (with respect to  $\Omega$ )*<sup>3</sup>. Here we used a different approach (and notations), indeed  $g^\Omega$  was constructed directly by using the isomorphism  $\text{Div}(X)_\mathbb{R} \cong G_0^\Omega(X)$ .

**Definition B.11.** Let  $g_1, g_2 \in G(C)$  such that  $\text{div}^G(g_1)$  and  $\text{div}^G(g_2)$  have no common components then the  $*$ -product between  $g_1$  and  $g_2$  is the real number:

$$g_1 * g_2 := \tilde{g}_1(\text{div}^G(g_2)) + \int_C dd^c(g_1)g_2,$$

where  $dd^c = \frac{1}{2\pi} \partial\bar{\partial}$ .

*Remark B.12.* It is necessary to assume that  $\text{div}^G(g_1)$  and  $\text{div}^G(g_2)$  have no common components otherwise  $\tilde{g}_1(\text{div}(g_2))$  wouldn't be well defined.

**Theorem B.13.** Let  $g_1, g_2 \in G(C)$  such that  $\text{div}^G(g_1)$  and  $\text{div}^G(g_2)$  have no common components, then  $g_1 * g_2 = g_2 * g_1$ .

*Proof.* See [15, Proposition 4.12]. □

**Corollary B.14.**  $g^\Omega(p, q) = g^\Omega(q, p)$  for any  $p \neq q$ .

*Proof.* By using the properties of the elements in  $G_0^\Omega$ , it is easy to verify that

$$\mathcal{G}^\Omega([p]) * \mathcal{G}^\Omega([q]) = g^\Omega(p, q); \quad \mathcal{G}^\Omega([q]) * \mathcal{G}^\Omega([p]) = g^\Omega(q, p).$$

Hence the conclusion follows immediately from Theorem B.13. □

Note that for any three different points  $p, q, t \in X$  and coefficients  $a, b \in \mathbb{R}$  we have that:

$$\mathcal{G}^\Omega(a[p] + b[q]) * \mathcal{G}^\Omega([t]) = a\mathcal{G}^\Omega([p]) * \mathcal{G}^\Omega([t]) + b\mathcal{G}^\Omega([q]) * \mathcal{G}^\Omega([t]).$$

Therefore if  $D = \sum_{p \in X} a_p [p]$  and  $E = \sum_{q \in X} b_q [q]$  are two real divisors of  $X$  with no common components, then it is customary to define:

$$g^\Omega(D, E) := \sum_{p \neq q} a_p b_q g^\Omega(p, q). \tag{23}$$

*Remark B.15.* The important point to emphasize here is that for Green functions  $g_1, g_2 \in G_0^\Omega$ , i.e. coming from some real divisors on  $X$ , the integral appearing in  $g_1 * g_2$  vanishes. This means that for such kind of Green functions, the nature of the  $*$ -product is “less analytic”, indeed it depends only on the value of  $g_1$  or  $g_2$  at a finite set of points.

## B.2 Arakelov intersection pairing

On each Riemann surface  $X_\sigma$  we fix a Kähler form  $\Omega_\sigma$  such that  $\int_{X_\sigma} \Omega_\sigma = 1$ , and we put  $\Omega := \{\Omega_\sigma\}_{\sigma \in B_\infty}$ . For any divisor  $D \in \text{Div}(X)$ ,  $D_\sigma := \varphi_\sigma^* D \in \text{Div}(X_\sigma)$  denotes its pullback through  $\varphi_\sigma$ . Consider the additive group  $\mathbf{G}(X) := \bigoplus_{\sigma \in B_\infty} G(X_\sigma)$  and its subgroup, depending on  $\Omega$ ,  $\mathbf{G}(X, \Omega) := \bigoplus_{\sigma \in B_\infty} G^{\Omega_\sigma}(X_\sigma)$ . By commodity we write any element of  $\mathbf{G}(X)$  (or of  $\mathbf{G}(X, \Omega)$ ) as a finite formal linear combination  $\sum_\sigma g_\sigma X_\sigma$  for  $g_\sigma \in \mathbf{G}(X)$  (or  $g_\sigma \in \mathbf{G}(X, \Omega)$ ).

**Definition B.16.** The group of *Arakelov divisors* on  $\widehat{X}$  is:

$$\text{Div}_{\text{Ar}}(X, \Omega) := \left\{ \left( D, \sum_\sigma g_\sigma X_\sigma \right) \in \text{Div}(X) \times \mathbf{G}(X, \Omega) : \text{div}^G(g_\sigma) = D_\sigma \right\}.$$

We often denote the element  $(0, X_\sigma) \in \text{Div}_{\text{Ar}}(X, \Omega)$  simply with the symbol  $X_\sigma$ .

<sup>3</sup>Actually the conditions which uniquely define  $g^\Omega$  in [2] and [1] are slightly different from the ones listed here, and moreover they may vary in other references. For instance it is common to find different constants for the differential Poisson equation, or the Green function might be defined as  $G = \exp(g^\Omega)$ . Of course these discrepancies are fixed when the Green function is applied for intersection theory.

It is important to understand the geometry lying behind the above apparently mysterious definition. Fix an Arakelov divisor  $(D, \sum_{\sigma} g_{\sigma} X_{\sigma})$ , by Theorem B.7 and Proposition B.8 we can write

$$g_{\sigma} = \mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}) + \alpha_{\sigma} \quad (24)$$

where  $\alpha_{\sigma} \in \mathbb{R}$  is uniquely determined. Figure 6 highlights the fact that  $D_{\sigma}$ , which is a finite set of points on  $X_{\sigma}$ , can be interpreted as the ‘‘prolongation’’ of  $D$  on the curve  $X_{\sigma}$ ; thus, it makes sense to define the Arakelov divisor

$$\bar{D} := \left( D, \sum_{\sigma} \mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}) X_{\sigma} \right) \in \text{Div}_{\text{Ar}}(X, \Omega)$$

which will be called *completion* of  $D$  in  $\hat{X}$  (this is consistent with the notion of completed horizontal curve given before). By equation (24) we have the following unique decomposition of  $(D, \sum_{\sigma} g_{\sigma} X_{\sigma})$  in  $\text{Div}_{\text{Ar}}(X)$ :

$$\left( D, \sum_{\sigma} g_{\sigma} X_{\sigma} \right) = \bar{D} + \sum_{\sigma} \alpha_{\sigma} X_{\sigma} \quad (25)$$

where the linear combination  $\sum_{\sigma} \alpha_{\sigma} X_{\sigma}$  can be evidently read as a ‘‘real divisor’’ on  $\hat{X}$  with support made of curves at infinity. In perfect analogy with the usual notion of divisor, equation (25) tells us that an Arakelov divisor can be interpreted as a formal linear combination of ‘‘curves’’ in  $\hat{X}$ , such that the coefficients of the curves at infinity are in  $\mathbb{R}$ . The presence of this real coefficients underlines once again the fact that the curves at infinity have an analytic nature. From the above discussion we recover the original definition of the group of Arakelov divisors given in [2] and [1]:

**Proposition B.17.** *There is an isomorphism of groups:*

$$\text{Div}_{\text{Ar}}(X, \Omega) \cong \text{Div}(X) \oplus \mathbb{R}^{(B_{\infty})}$$

*Proof.* Thanks to equation (25) we can define the isomorphism:

$$\left( D, \sum_{\sigma} g_{\sigma} X_{\sigma} \right) \mapsto D + \sum_{\sigma} \alpha_{\sigma} [\sigma].$$

□

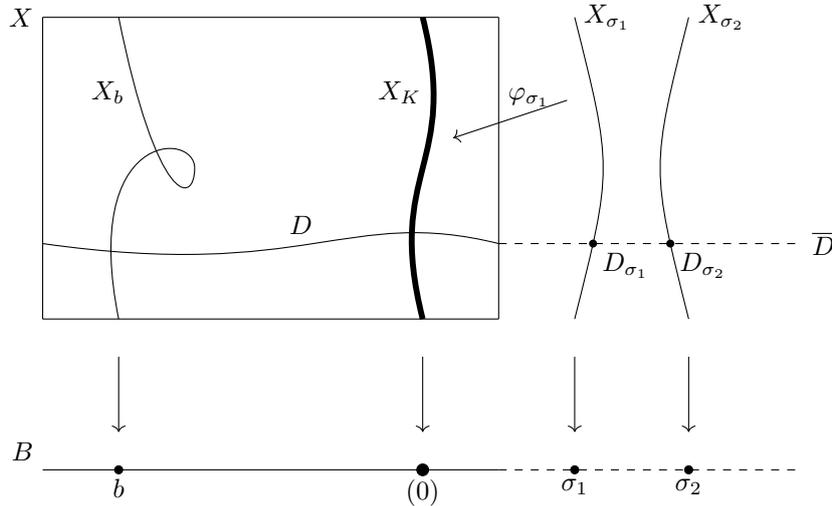


Figure 6: A schematic of an arithmetic surface  $\varphi : X \rightarrow B$  such that  $B_{\infty} = \{\sigma_1, \sigma_2\}$ .  $X_b$  is a vertical divisor over the closed point  $b$ ,  $D$  is a horizontal divisor such that  $D_{\sigma_1}$  and  $D_{\sigma_2}$  are prime divisors respectively on  $X_{\sigma_1}$  and  $X_{\sigma_2}$ .

Now we want to introduce the concept of principal Arakelov divisor, in other words we want to define an Arakelov divisor associated to an element of  $K(X)$ . Recall that  $K(X)$  is also the function field of  $X_K$ , so the morphism  $\varphi_{\sigma} : X_{\sigma} \rightarrow X_K$  induces a field embedding

$$\varphi_{\sigma}^{\#} : K(X) \hookrightarrow \mathbb{C}(X_{\sigma}).$$

For any rational function  $f \in K(X)$  we put by simplicity  $f_\sigma := \varphi_\sigma^\#(f)$ . Moreover let  $\mathcal{O}_\sigma$  be the sheaf of regular functions on  $X_\sigma$ , then as usual  $f_\sigma$  can be identified with a holomorphic map  $X_\sigma \rightarrow \mathbb{C}$  at all but finitely many points:

$$p \mapsto f_{\sigma,p} \mapsto \bar{f}_{\sigma,p} \in k(p) \cong \mathbb{C}$$

Then it is easy to see that  $-\log |f_\sigma|^2$  is a Green function on  $X_\sigma$  such that  $\partial\bar{\partial}(-\log |f_\sigma|^2) = 0$ , therefore  $-\log |f_\sigma|^2 \in G^{\Omega_\sigma}(X_\sigma)$ .

**Proposition B.18.** *Let  $f \in K(X)^\times$ , then  $\operatorname{div}^G(-\log |f_\sigma|^2) = (f)_\sigma$ , where  $(f)_\sigma$  is the pullback of the principal divisor  $(f)$ .*

*Proof.* Fix a point  $p \in X_\sigma$ , let  $x = \varphi_\sigma(p)$  and consider  $f$  as a rational function on  $X_K$ . If  $\varpi_\sigma$  is a local parameter in  $\mathcal{O}_{\sigma,p}$  and  $\varpi$  is a local parameter in  $\mathcal{O}_{X_K,x}$ , then

$$f_\sigma = \varpi_\sigma^{v_p(\varphi_\sigma^\#(\varpi))v_x(f)} u \quad \text{for } u \in \mathcal{O}_{\sigma,p}.$$

This implies that  $\operatorname{ord}_p^G(-\log |f_\sigma|^2) = v_p(\varphi_\sigma^\#(\varpi))v_x(f)$ , but  $v_p(\varphi_\sigma^\#(\varpi))$  is precisely the ramification index  $e_{\varphi_\sigma,p}$ , hence  $\operatorname{ord}_p^G(-\log |f_\sigma|^2) = e_{\varphi_\sigma,p}v_x(f)$ . So, we finally have:

$$\operatorname{div}^G(-\log |f_\sigma|^2) = \sum_{p \in X_\sigma} e_{\varphi_\sigma,p}v_{\varphi_\sigma(p)}(f)[p] = (f)_\sigma.$$

□

Now the following definition makes sense:

**Definition B.19.** Let  $f \in K(X)^\times$  be a rational function. It induces an Arakelov divisor in the following way:

$$(\widehat{f}) := \left( (f), \sum_\sigma -\log |f_\sigma|^2 X_\sigma \right) \in \operatorname{Div}_{\operatorname{Ar}}(X, \Omega).$$

The group

$$\operatorname{Princ}_{\operatorname{Ar}}(X, \Omega) := \left\{ (\widehat{f}) : f \in K(X) \right\}$$

is called the group of *principal Arakelov divisor* and  $\operatorname{CH}_{\operatorname{Ar}}^1(X, \Omega) := \frac{\operatorname{Div}_{\operatorname{Ar}}(X, \Omega)}{\operatorname{Princ}_{\operatorname{Ar}}(X, \Omega)}$  is the *Arakelov Chow group*. Two Arakelov divisor are said *linearly equivalent* if they are contained in the same class in  $\operatorname{CH}_{\operatorname{Ar}}^1(X, \Omega)$ .

Moreover for any principal Arakelov divisor  $(\widehat{f})$  we get the following decomposition:

$$(\widehat{f}) = (\overline{f}) + \sum_\sigma \left( \int_{X_\sigma} -\log |f_\sigma|^2 \Omega_\sigma \right) X_\sigma.$$

**Proposition B.20.** *Let  $D, E$  be two finite divisors on  $X$  with no common components, then for any  $\sigma \in B_\infty$  the divisors  $D_\sigma$  and  $E_\sigma$  on  $X_\sigma$  have no common components.*

*Proof.* Omitted □

Let's denote as  $\Upsilon_{\operatorname{Ar}} \subset \operatorname{Div}_{\operatorname{Ar}}(X, \Omega) \times \operatorname{Div}_{\operatorname{Ar}}(X, \Omega)$  the set of couples of Arakelov divisors with no common components on  $X$ , then we can define the Arakelov intersection pairing on  $\Upsilon_{\operatorname{Ar}}$ :

**Definition B.21.** Let  $\widehat{D} := (D, \sum_\sigma g_\sigma X_\sigma)$ ,  $\widehat{E} := (E, \sum_\sigma l_\sigma X_\sigma)$  be two Arakelov divisors such that  $(\widehat{D}, \widehat{E}) \in \Upsilon_{\operatorname{Ar}}$ . Thanks to Proposition B.20 we can define an Arakelov divisor on  $B$ :<sup>4</sup>

$$\left\langle \widehat{D}, \widehat{E} \right\rangle_{\operatorname{Ar}} := \langle D, E \rangle + \sum_\sigma g_\sigma * l_\sigma[\sigma] \in \operatorname{Div}_{\operatorname{Ar}}(B)$$

where

$$\langle D, E \rangle := \varphi_* i(D, E) = \sum_{x \in X} [k(x) : k(\varphi(x))] i_x(D, E) [\varphi(x)]$$

<sup>4</sup>Note that we assume  $D$  and  $E$  to have no common components in order to ensure that the  $*$ -product between green functions is well defined for any  $\sigma \in B_\infty$ .

and  $*$  is the product between Green functions. If  $\widehat{d} = \sum_{\mathfrak{p} \in B} n_{\mathfrak{p}} [\mathfrak{p}] + \sum_{\sigma \in B_{\infty}} \alpha_{\sigma} [\sigma]$  is an Arakelov divisor on the base  $B$ , its degree is defined as:

$$\deg_{\text{Ar}}(\widehat{d}) := \sum_{\mathfrak{p} \in B} n_{\mathfrak{p}} \log \mathfrak{N}(\mathfrak{p}) + \frac{1}{2} \sum_{\sigma \in B_{\infty}} \epsilon_{\sigma} \alpha_{\sigma}.$$

In particular we use the notation  $D.E := \deg_{\text{Ar}}(\langle\langle D, E \rangle\rangle)$ , and the *Arakelov intersection number* of  $\widehat{D}$  and  $\widehat{E}$  is:

$$\widehat{D}.\widehat{E} := \deg_{\text{Ar}}(\langle\langle \widehat{D}, \widehat{E} \rangle\rangle_{\text{Ar}}) = D.E + \frac{1}{2} \sum_{\sigma} \epsilon_{\sigma} g_{\sigma} * l_{\sigma} \in \mathbb{R},$$

The following proposition summarizes some properties of the Arakelov intersection pairing:

**Proposition B.22.** *Let  $(\widehat{D}, \widehat{E}), (\widehat{D}_j, \widehat{E}_j) \in \Upsilon_{\text{Ar}}$  with  $j = 1, 2$ , then*

- (1)  $\widehat{D}.\widehat{E} = \widehat{E}.\widehat{D}$  (*symmetry*).
- (2)  $(\widehat{D}_1 + \widehat{D}_2).(\widehat{E}_1 + \widehat{E}_2) = \sum_{j,k=1}^2 \widehat{D}_j.\widehat{E}_k$  ( *$\mathbb{Z}$ -bilinearity*).
- (3) *If  $\widehat{D} = (D, \sum_{\sigma} g_{\sigma} X_{\sigma})$  and  $f \in K(X)^{\times}$  such that  $(D, (f)) \in \Upsilon$ , then*

$$\langle\langle \widehat{D}, (\widehat{f}) \rangle\rangle_{\text{Ar}} = (\widehat{N_D(f)}) \in \text{Princ}_{\text{Ar}}(B).$$

*In particular  $\widehat{D}.\widehat{(f)} = 0$ .*

*Proof.* See [15, section 4.4]. □

The Arakelov intersection number can be extended to an intersection pairing on the whole  $\text{Div}_{\text{Ar}}(X, \Omega)$  and induces a natural intersection pairing on  $\text{CH}_{\text{Ar}}^1(X, \Omega)$ .

**Proposition B.23.** *The Arakelov intersection number extends to any two Arakelov divisors in  $\text{Div}_{\text{Ar}}(X, \Omega) \times \text{Div}_{\text{Ar}}(X, \Omega)$  and moreover descends naturally to pairing on  $\text{CH}_{\text{Ar}}^1(X, \Omega) \times \text{CH}_{\text{Ar}}^1(X, \Omega)$ .*

*Proof.* See [15, section 4.4]. □

Now we interpret the Arakelov intersection pairing in a more geometric way by using the decomposition given in equation (25). Fix two Arakelov divisors  $\widehat{D}, \widehat{E} \in \Upsilon_{\text{Ar}}$ , then we can write

$$\begin{aligned} \widehat{D} &= \overline{D} + \sum_{\sigma} \alpha_{\sigma} X_{\sigma} = \left( D, \sum_{\sigma} \mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}) X_{\sigma} \right) + \left( 0, \sum_{\sigma} \alpha_{\sigma} X_{\sigma} \right), \\ \widehat{E} &= \overline{E} + \sum_{\sigma} \beta_{\sigma} X_{\sigma} = \left( E, \sum_{\sigma} \mathcal{G}^{\Omega_{\sigma}}(E_{\sigma}) X_{\sigma} \right) + \left( 0, \sum_{\sigma} \beta_{\sigma} X_{\sigma} \right). \end{aligned}$$

In order to find explicitly  $\widehat{D}.\widehat{E}$ , by bilinearity and symmetry of the intersection pairing it is enough to understand how calculate the following three terms:

- (i)  $\overline{D}.\overline{E}$ ; namely the intersection of two completed divisors.
- (ii)  $\overline{D}.(0, \sum_{\sigma} \beta_{\sigma} X_{\sigma})$ ; namely the intersection between a completed divisor and a divisor at infinity. Clearly  $(0, \sum_{\sigma} \alpha_{\sigma} X_{\sigma}).\overline{E}$  is obtained in the same way.
- (iii)  $(0, \sum_{\sigma} \alpha_{\sigma} X_{\sigma}).(0, \sum_{\sigma} \beta_{\sigma} X_{\sigma})$ ; that is the intersection of divisors composed only by curves at infinity.

For (i) let's evaluate  $\mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}) * \mathcal{G}^{\Omega_{\sigma}}(E_{\sigma})$ . By the bare definition of the  $*$ -product and  $g^{\Omega_{\sigma}}$ :

$$\mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}) * \mathcal{G}^{\Omega_{\sigma}}(E_{\sigma}) = g^{\Omega_{\sigma}}(D_{\sigma}, E_{\sigma}) + \int_{X_{\sigma}} dd^c(\mathcal{G}^{\Omega_{\sigma}}(D_{\sigma})) \mathcal{G}^{\Omega_{\sigma}}(E_{\sigma}),$$

but since  $\mathcal{G}^{\Omega_{\sigma}}(D_{\sigma}), \mathcal{G}^{\Omega_{\sigma}}(E_{\sigma}) \in G_0^{\Omega_{\sigma}}(X_{\sigma})$ , it is straightforward to verify that the integral on the right hand side is 0. Therefore we get:

$$\overline{D}.\overline{E} = D.E + \frac{1}{2} \sum_{\sigma} \epsilon_{\sigma} g^{\Omega_{\sigma}}(D_{\sigma}, E_{\sigma}). \quad (26)$$

In order to calculate (ii) we need  $\mathcal{G}^{\Omega\sigma}(D_\sigma) * \beta_\sigma$ :

$$\mathcal{G}^{\Omega\sigma}(D_\sigma) * \beta_\sigma = \beta_\sigma * \mathcal{G}^{\Omega\sigma}(D_\sigma) = \beta_\sigma \deg(D_\sigma) + \int_{X_\sigma} dd^c(\beta_\sigma) \mathcal{G}^{\Omega\sigma}(D_\sigma) = \beta_\sigma \deg(D_\sigma),$$

thus we obtain

$$\overline{D} \cdot (0, \sum_\sigma \beta_\sigma X_\sigma) = \frac{1}{2} \sum_\sigma \epsilon_\sigma \beta_\sigma \deg(D_\sigma). \quad (27)$$

Finally (iii) is trivial since  $\alpha_\sigma * \beta_\sigma = 0$  and we have:

$$(0, \sum_\sigma \alpha_\sigma X_\sigma) \cdot (0, \sum_\sigma \beta_\sigma X_\sigma) = 0. \quad (28)$$

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## Notes and Errata

This section collects some notes and a list of errata to the published version of the paper in: *Journal of Number Theory*, 211 (2020), pp. 235–296. We thank Ivan Fesenko for pointing out most of the unclear or inaccurate parts of the paper.

### General comments

**(i) Real curves at infinity over real places.** We can distinguish two types of archimedean places of a number field: real and complex ones; if one forgets about this distinction and works just with  $\mathbb{C}$ , some crucial topological properties of adèles don't hold anymore. The same phenomenon occurs in our two dimensional theory: over real places we must consider real curves, and over complex places we have the usual fibres at infinity (i.e. Riemann surfaces) of Arakelov geometry. Unfortunately in the paper we didn't distinguish between complex and real fibres, but we considered the complex structure over each curve at infinity. This leads to some problems in the proof that  $A_{\widehat{01}} = A_{\widehat{01}}^\perp$  when we reduce to one dimensional adèles to deal the case of horizontal curves. Clearly everything works well when  $K$  is a number field with only complex non-real embeddings, but for the general case we need some small modifications in the general setting. If  $\sigma \in B_\infty$  then we denote with  $K_\sigma$  the archimedean completion of  $K$ , which obviously can be either  $\mathbb{R}$  or  $\mathbb{C}$ . We then consider the following curve over  $K_\sigma$ :

$$X_\sigma := X \times_\sigma \text{Spec } K_\sigma.$$

Notice that when  $K_\sigma = \mathbb{C}$ , then clearly  $X_\sigma$  is a Riemann surface, otherwise  $X_\sigma$  is a real curve. With the symbol  $K_\sigma(X_\sigma)$  we denote the function field of  $X_\sigma$ . Throughout the paper, the object  $\mathbb{C}(X_\sigma)$  must be *everywhere* replaced by  $K_\sigma(X_\sigma)$ .

**(ii) Transcendental points on  $X_\sigma$  don't come from horizontal curves.** In the paper we wrongly assumed that any closed point  $p \in X_\sigma$  lies on exactly two curves: one horizontal and one vertical (which is  $X_\sigma$  itself), but this is true if and only if  $p$  is an algebraic point. In fact if  $p$  is a transcendental point, then the base change morphism  $\varphi_\sigma : X_\sigma \rightarrow X_K$  maps  $p$  to the generic point of  $X_K$  which doesn't correspond to any horizontal divisor on the surface  $X$ . It means that transcendental points are contained *only in the curve*  $X_\sigma$ . This leads to some minor changes in the theory of adèles that will be explained below in all details. Nevertheless the statements and the proofs of the main results don't change significantly.

**(iii) Continuity of adelic residue and pairing.** In proposition 3.5 we showed that the adelic residue  $\xi^\omega : \mathbf{A}_{\widehat{X}} \rightarrow \mathbb{T}$  is sequentially continuous by using only the bare definition of the topology on  $\mathbf{A}_{\widehat{X}}$ . But we can say more about  $\xi^\omega$  if we use some deeper results of the paper. In the proof of the self-duality of  $\mathbf{A}_{\widehat{X}}$ , we explicitly constructed a standard character  $\mathbf{A}_{\widehat{X}}$  first by a lifting process, and then by working with the restricted product. After a closer look, one can notice that such character is exactly  $\xi^\omega$  for  $\omega = 1dt$ . It follows that  $\xi^\omega$  is indeed a character, and not just a sequentially continuous map. It follows that also the differential pairing  $d_\omega : \mathbf{A}_{\widehat{X}} \times \mathbf{A}_{\widehat{X}} \rightarrow \mathbb{T}$  is continuous.

**(iv) On differential forms along vertical curves and uniformizing parameters.** If  $y$  is a vertical curve, and  $\alpha \in \mathbf{A}_X$  there is a misleading usage of the symbol  $dt$  when we write an element  $\alpha_{x,y} dt \in \Omega_{x,y}$ . In fact, along a vertical curve  $y$  the parameter  $t \in K_{x,y}$  depends on the point  $x \in y$  (unlike for horizontal curves). Remember that for vertical curves the 2-dimensional local fields involved are of mixed characteristic, for instance of the type  $K_p\{\{t\}\}$ ; so  $t$  is not a uniformizing parameter (see page 245, line -2), and it shouldn't be confused with  $t_y$  that is equal to  $p$ . To be formally correct, in such cases one should read  $\alpha_{x,y} dt(x) \in \Omega_{x,y}$  or even  $\alpha_{x,y} dt(x, y) \in \Omega_{x,y}$  when also  $y$  varies. Moreover, often in the paper one can find something like  $\text{res}_{x,y}(\alpha_{x,y})$  but the formal meaning is clearly  $\text{res}_{x,y}(\alpha_{x,y} dt(x, y))$ .

### Comments with detailed pointers

The pointers refer to the published version of the paper.

**page 238, -13.** By (i),  $X_\sigma$  might not be a Riemann surface but a real curve.

page 238, -11. The equation

$$\mathbf{A}_{\widehat{X}} = \mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_\sigma} \oplus \mathbf{A}_{X_\sigma}).$$

is not true, but it should be:

$$\mathbf{A}_{\widehat{X}} = \mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_{\overline{K},\sigma}} \oplus \mathbf{A}_{X_\sigma}).$$

where  $\mathbf{A}_{X_{\overline{K},\sigma}}$  is the ring of adeles attached to  $X_{\overline{K},\sigma}$ .

**Page 241, Proposition 1.1.** The choice of a decreasing sequence  $\dots \supset H_i \supset H_{i+1} \dots$  might seem a bit unnatural for a direct limit. Nevertheless we insist on this notation as we want to apply the proposition to the decreasing sequence of spaces  $\mathbb{A}_y^{(r)}$  defined later. Obviously, to define  $\varinjlim_{i \in \mathbb{Z}} H_i$  we need to consider  $\mathbb{Z}$  with the relation  $i \preceq j$  if and only if  $i \geq j$ .

**Page 243.** As above,  $X_\sigma$  is obtained as base change with respect to  $\text{Spec } K_\sigma$ . Furthermore at the end of the page some crucial details about the base change map  $X_\sigma \rightarrow X_K$  have been added.

**Page 246, line 1.** The sentence “(...) a uniformizing parameter  $t = t_y$  of  $K_y$  (...)” is dangerously misleading, and must be replaced by “(...) a uniformizing parameter  $t_y$  of  $K_y$  (...)”. In fact the parameter  $t$  for mixed characteristic 2-dimensional local fields was used to denote another object. Actually,  $t = t_y$  *only* for horizontal curves.

**Page 249, line 6.** Remove the confusing sentence: “and any Laurent power series (...) is a truly convergent series”.

**page 249, lines 17 and -5.** As explained in (ii), it is not true that a transcendental point  $p \in X_\sigma$  “sits” on a horizontal curve, since horizontal curves of the arithmetic surface correspond to *closed points* of  $X_K$ . In this, case since  $p$  is transcendental, its image through the base change map is the generic point of  $X_K$ , which is not a closed point.

**Page 250, definition of  $K_{p,\sigma}$ .** For what we have said in (i): if  $\sigma$  is complex we have  $K_{p,\sigma} \cong \mathbb{C}((t))$ , whereas if  $\sigma$  is real we obtain  $K_{p,\sigma} \cong \mathbb{R}((t))$ . We still endow  $K_{p,\sigma}$  with the ind/pro-topology (remember that we are making a choice for the uniformizer). So, Remark 2.1 must be ignored.

**Page 250, line -6, definition of  $\mathbf{A}_{\overline{y}}$ .** The ring  $\mathbf{A}_{\overline{y}}$  must be the ring of adeles of the number field  $k(y)$  and not the slightly bigger version described in the paper.

**Page 254, Proposition 2.9.** The correct equality is:

$$\mathbf{A}_{\widehat{X}} = \mathbf{A}_X \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_{\overline{K},\sigma}} \oplus \mathbf{A}_{X_\sigma}).$$

because of (ii).

**Page 255,  $A_{\widehat{02}}$  and  $A_{\widehat{0}}$ .** The definitions of  $A_{\widehat{02}}$  and  $A_{\widehat{0}}$  need to be modified because of (ii):  $\Delta_{p,\sigma}$  is the diagonal of  $K_{p,\overline{y}} \times K_{p,\sigma}$  if  $p \in X_{\overline{K},\sigma}$ , otherwise we put  $\Delta_{p,\sigma} = \mathcal{O}_{p,\sigma}$ . This modifies  $A_{\widehat{02}}$  since  $\Delta_{p,\sigma}$  is its part at infinity. We put  $A_{\widehat{0}} = K(\widehat{X})$ , where we clearly consider the diagonal embedding  $K(X) \hookrightarrow \mathbf{A}_{\widehat{X}}$ . Moreover remark 2.12 must be ignored.

**Page 255, line -4.** We added a proof of the equality  $A_{\widehat{0}} = A_{\widehat{01}} \cap A_{\widehat{02}}$ .

**Page 256.** The presentation of the residue maps has been improved: the distinction between the different cases is now more explicit.

**Page 257, line 5.** The equation must be:

$$\text{Cres}_{x,\bar{y}} := \psi_b \circ \text{res}_{x,\bar{y}} : \Omega_{x,\bar{y}}^1 \rightarrow \mathbb{T}$$

so  $\text{res}_{x,y}$  is replaced by  $\text{res}_{x,\bar{y}}$ .

**Page 258, line 1.** Added the reference to [24] for the definition of residues on curves.

**Page 259, item (2) of theorem 3.3.** The statement should be: “Let  $p \in X_{\bar{K},\sigma} \subset X_\sigma$ , and let ...”. The (trivial) case of transcendental points is considered separately because of (ii).

**Page 261, line 12.** The following stronger equality is true:

$$\lim_{n \rightarrow \infty} \sum_{\substack{y \subset X_b, \\ x \in y}} \text{res}_{x,y} \left( \beta_{x,y}^{(n)} dt \right) = 0 \quad (29)$$

*Proof.* Fix the vertical curve  $y$  and consider the  $y$ -components  $\beta_y^{(n)}$  of the adelic sequence  $\beta^{(n)}$ . Since  $\beta_y^{(n)} \rightarrow 0$  as element in  $\mathbb{A}_y$ , it follows that the series converges uniformly with respect to  $n$ . Therefore it is possible to exchange the limit and the summation in (29).  $\square$

**Page 264, line 7.** The definition of  $C$  is incorrect. One must take:

$$C = \prod_{\bar{y} \in S} C_{\bar{y}} \times \prod_{\bar{y} \notin S} M_{\bar{y}} \times \prod_{\sigma \in B_\infty} C_\sigma$$

where  $M_{\bar{y}}$  is a compact subgroup of  $\mathbb{A}_{\bar{y}}^{(0)}$ .

**Page 268, line -6.** “is contained a basic” should be “is contained in a basic”. Two lines below remove “pen” after “open”.

**Page 273, Lemma 5.7** The lemma, as stated in the paper is false, in fact we only showed one containment, and not the equality. Nevertheless, we use Lemma 5.7 only at end of the proof of Lemma 5.8, so for our purposes (see the comment below) we can state and prove a weaker and easier version:

**Lemma** (New version of Lemma 5.7.). *Let  $F$  be a complete discrete valuation field, then:*

$$\text{Frac}(\mathcal{O}_F[[t]]) = \left\{ \sum_{i \geq m} a_i t^i \in F((t)) : \inf_i v(a_i) > -\infty \right\}.$$

*Proof.* ( $\supseteq$ ) Let  $f = \sum_{i \geq m} a_i t^i$  such that  $k = \inf_i v(a_i)$ , and let  $\varpi$  be a uniformizing parameter of  $F$ . Then  $\varpi^{-k} f \in \mathcal{O}_F((t))$  and the required inclusion follows easily.

( $\subseteq$ ) Let  $f \in \mathcal{O}_F[[t]] \setminus \{0\}$ , then for  $r, s \geq 0$  we can obviously write  $f = \varpi^r t^s \sum_{i \geq 0} b_i t^i$  such that  $b_0 \in \mathcal{O}_F^\times$ . It follows that  $\sum_{i \geq 0} b_i t^i$  is invertible, therefore we only need to enlarge  $\mathcal{O}_F[[t]]$  with the inverses of the elements of the type  $\varpi^r t^s$ ; but such inverses clearly satisfy the required condition about the infimum.  $\square$

**Page 275, Proof of Lemma 5.8, line -3.** Once that we have shown  $a_{x,q_v} \in K_b((t))$ , we use the fact that by hypothesis  $a_{x,q_v} \in K_{x,q_v}$ . Since  $K_{x,q_v}$  is of mixed characteristic, the valuations on the coefficients of  $a_{x,q_v}$  are bounded from below, therefore we can use the new version of lemma 5.7 to conclude that  $a_{x,q_v} \in \text{Frac}(\mathcal{O}_b[[t]]) = K'_x$ .

**Page 277, line 5.** With the modified definition of  $A_{\widehat{02}}$  at infinity we have to distinguish the cases when  $p$  is algebraic or transcendental.

**Page 278, line -8.** “an idelic” instead of “ad idelic”.

**Section 6.** Because of (ii), we lift the Arakelov pairing to the space  $\mathbf{A}_X^\times \oplus \prod_{\sigma \in B_\infty} (\mathbf{A}_{X_\sigma}^\times \oplus \mathbf{A}_{X_\sigma}^\times)$  which is slightly bigger than  $\mathbf{A}_{\widehat{X}}^\times$ . Moreover the map  $\Theta$  is  $(a, b) \mapsto -|b| \log(a\bar{a})$ , so all other formulas change accordingly.

**Page 285, line 14.** The construction of the ind/pro topology on  $R((t))$  works with few changes also if  $R$  is a topological field, without the assumption of linearity. This has been briefly explained in the last remark of the appendix.

**Page 291, caption of figure 5.** The figure doesn't depict the arithmetic surface over  $B = \text{Spec } \mathbb{Z}[i]$ , since  $\mathbb{Q}(i)$  has only one complex embedding up to conjugation. One for example can take  $B = \text{Spec } O_K$  with  $K = \mathbb{Q}(\sqrt{2}, i)$ .