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ZETA FUNCTIONS, EXCISION IN CYCLIC COHOMOLOGY AND INDEX PROBLEMS

RUDY RODSPHON

ABSTRACT. The aim of this paper is to show how zeta functions and excision in cyclic cohomology may be combined to obtain index theorems. In the first part, we obtain an index formula for "abstract elliptic pseudodifferential operators" associated to spectral triples, in the spirit of the one of Connes and Moscovici. This formula is notably well adapted when the zeta function has multiple poles. The second part is devoted to give a concrete realization of this formula by deriving an index theorem on the simple, but significant example of Heisenberg elliptic operators on a trivial foliation, which are in general not elliptic but hypoelliptic. The formula obtained is an extension of an index formula due to Fedosov.

KEYWORDS. Cyclic cohomology, K-theory, Index theory, Pseudodifferential operators

MSC. 19D55, 19K56, 58J42, 46L87

INTRODUCTION

Several years ago, Connes and Moscovici obtained in [4] a general index formula given in terms of residues of zeta functions, working with the so-called *spectral triples*. A major advance was made since this formalism enlarges index theory to the more general context of the transverse geometry of foliations, where the interesting pseudodifferential operators are hypoelliptic without necessary being elliptic. Let us be a little more precise on this general formula. Connes and Moscovici constructed a Residue Cocycle on the algebra of the spectral triple, whose periodic cyclic cohomology class is the Chern-Connes character (cf. [2] or [3]). An important feature of this cocycle is to remain unchanged when the "Dirac operator" D is perturbed by a smoothing operator, because it involves residues of zeta functions. This is not the case for the representative of the Chern-Connes character constructed using Fredholm modules and the operator $F = D|D|^{-1}$ (cf. [2]), since it involves the operator trace. In this sense, the Residue Cocycle is a better representative of the Chern-Connes character and is more convenient to derive local index formulas.

In the spirit of the techniques developed by Connes and Moscovici, we give an abstract index formula of a different flavor, which turns out to be useful to calculate the index of abstract elliptic pseudodifferential operators associated to regular spectral triples. The formula is also given by residues of zeta functions and a certain cyclic cocycle. Nonetheless, there is one important difference since our cocycle is defined not only on an "algebra of smooth functions" as in the Connes-Moscovici formula, but directly on the algebra of formal symbols of the pseudodifferential operators considered. We then illustrate on a simple but interesting example how such a formula may amount to topological index formulas. Let us give an overview of the paper.

Section 1 serves to recall some material about Higson's formalism (cf. [7]) about algebras of abstract differential operators and its relation with (regular) spectral triples. Following [12], this allows to develop an abstract pseudodifferential calculus and a notion of ellipticity which covers many interesting examples. We shall focus on the example of Connes and Moscovici on foliations, involving the Heisenberg pseudodifferential calculus.

The aim of Section 2 is to study the index theory in this context. More precisely, we construct a cyclic 1-cocycle on algebras of abstract pseudodifferential operators which generalizes the Radul cocycle defined for any closed manifold M . This cocycle was introduced by Radul in the context of Lie algebra cohomology (cf. [11]). The two important ingredients to construct this cocycle are, on the one hand, that the zeta function of a (classical) pseudodifferential operator on M has a meromorphic extension to the complex plane, whose set of poles is at most simple and discrete. This allows the use of the Wodzicki-Guillemin residue. On the other hand, one uses the pseudodifferential extension and excision in periodic cyclic cohomology to push the trace on regularizing operators on M , viewed as a cyclic 0-cocycle, to a cyclic 1-cocycle on the algebra of formal symbols on M . Excision in periodic cyclic cohomology then gives an index formula for elliptic pseudodifferential operators, by compatibility with excision in K -theory.

This construction is then extended to the abstract setting recalled in Section 1, and we obtain a cyclic 1-cocycle which generalizes the Radul cocycle in contexts where the zeta function exhibits multiple poles.

THEOREM 0.1. *Let $\Psi = \Psi(\Delta)$ be an algebra of abstract pseudodifferential operators on a Hilbert space H , and consider the pseudodifferential extension*

$$0 \longrightarrow \Psi^{-\infty} \longrightarrow \Psi \longrightarrow \mathcal{S} = \Psi/\Psi^{-\infty} \longrightarrow 0$$

Suppose that the pole at zero of the zeta function is of order $p \geq 1$. Then, the image $\partial[\text{Tr}] \in \text{HP}^1(\mathcal{S})$ of the operator trace $[\text{Tr}] \in \text{HP}^0(\Psi^{-\infty})$ by excision in periodic cyclic cohomology is represented by the following cyclic 1-cocycle :

$$c(a_0, a_1) = \int_1^1 a_0 \delta(a_1) - \frac{1}{2!} \int_2^2 a_0 \delta^2(a_1) + \dots + \frac{(-1)^{p-1}}{p!} \int_p^p a_0 \delta^p(a_1)$$

where $\delta(a) = [\log \Delta^{1/r}, a]$ and $\delta^k(a) = \delta^{k-1}(\delta(a))$ is defined by induction. The r denotes the "order of Δ ".

Here, $\Psi^{-\infty}$ is the algebra of regularizing operators associated to Ψ , i.e elements of all order. The \int^k are "higher Wodzicki residues" defined in Proposition 1.11.

In Section 3, we show on an example how the results of the previous section may lead to index formulas, in the spirit of the Atiyah-Singer theorem. The example we work on is that of a trivial foliation $\mathbb{R}^p \times \mathbb{R}^q$, dealing with the Heisenberg pseudodifferential calculus. Even if this example is simple, it is also relevant for at least three reasons : Firstly, it allows to deal with hypoelliptic (non-elliptic) operators. Secondly, one can see how this leads to a purely algebraic approach of index theory, thanks to Wodzicki residue trace. Thirdly, the philosophy of the construction given is useful to understand how to adapt the techniques developed in [9] to treat for example the general case of foliations (whose leaves are not necessarily compact). One interesting perspective is to obtain an index formula in the context of the transverse geometry of foliations, which would to an approach different from the one of Connes and Moscovici in [5].

When dealing with the Radul cocycle, the main obstacle is that the formulas arising are, except in low dimensions, rather complicated. It is not obvious at all to obtain directly topological index formulas which depend only on the principal symbol. To cope with this difficulty, the general idea is to construct (B, b) -cocycles of higher degree which are cohomologous to the Radul cocycle in the (B, b) -bicomplex. These (B, b) -cocycles are shown to be more easily computable in the highest degree, for a reason that will be understood later. We give two ways of constructing these cocycles. In the first construction, we introduce homogeneous (B, b) -cocycles on regularizing operators, in many points similar to the cyclic cocycles associated to Fredholm modules given by Connes. The game still consists in pushing them to (inhomogeneous) (B, b) -cocycles on the algebra of Heisenberg formal symbols, using a zeta function regularisation of the trace and excision.

The second construction involves Quillen's cochain theory from [10]. The interest in using this formalism stands in the way we obtain the desired cocycles, as we do not have to go through the algebra of regularizing operators first. Therefore, this method is completely algebraic.

Let $S_H^0(\mathbb{R}^n)$ be the associated algebra of Heisenberg formal symbols of order 0, and denote by

$$\sigma : S_H^0(\mathbb{R}^n) \longrightarrow C^\infty(S_H^*\mathbb{R}^n)$$

the Heisenberg principal symbol map. Here, $S_H^*\mathbb{R}^n$ denotes the "Heisenberg cosphere bundle", which is defined in Section 1.6. Then, the main result of the section can be stated as follows :

THEOREM 0.2. *The Radul cocycle is (B, b) -cohomologous to the homogeneous (B, b) -cocycle on $S_H^0(\mathbb{R}^n)$ defined by*

$$\Psi_{2n-1}(a_0, \dots, a_{2n-1}) = -\frac{1}{(2\pi i)^n} \int_{S_H^*\mathbb{R}^n} \sigma(a_0) d\sigma(a_1) \dots d\sigma(a_{2n-1})$$

As an immediate corollary, we obtain the following index theorem, which extends an index formula for elliptic operators on Euclidean spaces due to Fedosov (cf. [6]).

THEOREM 0.3. *Let $P \in M_N(\Psi_H^0(\mathbb{R}^n))$ be a Heisenberg elliptic pseudodifferential operator of formal symbol $u \in GL_N(S_H^0(\mathbb{R}^n))$, and $[u] \in K_1(S_H^0(\mathbb{R}^n))$ its (odd) K -theory class. Then, we have a formula for the Fredholm index of P :*

$$\text{Ind}(P) = \text{Tr}(\text{Ind}[u]) = \frac{(-1)^n (n-1)!}{(2\pi i)^n (2n-1)!} \int_{S_H^*\mathbb{R}^n} \text{tr}(\sigma(u)^{-1} d\sigma(u) (d\sigma(u)^{-1} d\sigma(u))^{n-1})$$

In other words, the index of P is given by the evaluation of the fundamental class of $S_H^*(\mathbb{R}^n)$ on the (odd) Chern character of its Heisenberg principal symbol.

1. ABSTRACT DIFFERENTIAL OPERATORS AND TRACES

In this part, we recall the Abstract Differential Operators formalism developed by Higson in [7] to simplify the proof of the Connes-Moscovici local index formula [4]. This is actually another way of defining regular spectral triples. For details, the reader may refer to [7] or [12].

1.1. Abstract Differential Operators. Let H be a (complex) Hilbert space and Δ be an unbounded, positive and self-adjoint operator acting on it. To simplify matters, we suppose that Δ has a compact resolvent. We denote by H^∞ the intersection

$$H^\infty = \bigcap_{k=0}^{\infty} \text{dom}(\Delta^k)$$

where dom stands for the domain of a unbounded operator.

DEFINITION 1.1. An algebra $\mathcal{D}(\Delta)$ of *abstract differential operators* associated to Δ is an algebra of operators on H^∞ fulfilling the following conditions

- (i) The algebra $\mathcal{D}(\Delta)$ is filtered,

$$\mathcal{D}(\Delta) = \bigcup_{q=0}^{\infty} \mathcal{D}_q(\Delta)$$

that is $\mathcal{D}_p(\Delta) \cdot \mathcal{D}_q(\Delta) \subset \mathcal{D}_{p+q}(\Delta)$. We shall say that an element $X \in \mathcal{D}_q(\Delta)$ is an *abstract differential operator of order at most q* . The term *differential order* will be often used for the order of such operators.

- (ii) There is a $r > 0$ ("the order of Δ ") such that for every $X \in \mathcal{D}_q(\Delta)$, $[\Delta, X] \in \mathcal{D}_{r+q-1}(\Delta)$.

To state the last point, we define, for $s \in \mathbb{R}$, the s -Sobolev space H^s as the subspace $\text{dom}(\Delta^{s/r})$ of H , which is a Hilbert space when endowed with the norm

$$\|v\|_s = (\|v\|^2 + \|\Delta^{s/r}v\|^2)^{1/2}$$

(iii) *Elliptic estimate.* If $X \in \mathcal{D}_q(\Delta)$, then, there is a constant $\varepsilon > 0$ such that

$$\|v\|_q + \|v\| \geq \varepsilon \|Xv\|, \forall v \in H^\infty$$

Having Gårding's inequality in mind, the elliptic estimate exactly says that $\Delta^{1/r}$ should be thought as an "abstract elliptic operator" of order 1. It also says that any differential operator X of order q can be extended to a bounded operator from H^{s+q} to H^s . This last property will be useful to define pseudodifferential calculus in this setting.

One example to keep in mind is the case in which Δ is a Laplace type operator on a closed Riemannian manifold M . Here, H^∞ consists of the smooth functions on M , $r = 2$ and $\mathcal{D}(\Delta)$ is simply the algebra of differential operators. The H^s are the usual Sobolev space and we have an elliptic estimate. In fact, the definition above is an abstraction of this example, but it can be adapted to many more situations, for instance the case of foliations, on which we shall focus more in detail.

1.2. Correspondence with spectral triple. Let (A, H, D) a spectral triple (cf. [4] or [7]). One may construct an algebra of abstract differential operators $\mathcal{D} = \mathcal{D}(A, D)$ inductively as follows :

$$\begin{aligned} \mathcal{D}_0 &= \text{algebra generated by } A \text{ and } [D, A] \\ \mathcal{D}_1 &= [\Delta, \mathcal{D}_0] + \mathcal{D}_0[\Delta, \mathcal{D}_0] \\ &\vdots \\ \mathcal{D}_k &= \sum_{j=1}^{k-1} \mathcal{D}_j \cdot \mathcal{D}_{k-j} + [\Delta, \mathcal{D}_{k-1}] + \mathcal{D}_0[\Delta, \mathcal{D}_{k-1}] \end{aligned}$$

Let δ be the unbounded derivation $\text{ad}|D| = [|D|, \cdot]$ on the algebra $\mathcal{B}(H)$ of bounded operators on H . The spectral triple (A, H, D) is said *regular* if $A, [D, A]$ are included in $\bigcap_{n=1}^{\infty} \text{dom } \delta^n$. The following theorem of Higson makes the bridge between algebras of abstract differential operators and spectral triples.

THEOREM 1.2. (Higson, [7]). *Suppose that A maps H^∞ into itself. Then, the spectral triple (A, H, D) is regular if and only if the elliptic estimate of Definition 1.1 holds.*

Regularity in spectral triples may be viewed as an assumption allowing to control some asymptotic expansions of "pseudodifferential operators", as we shall see in the next paragraph from the perspective of the elliptic estimate.

1.3. Zeta Functions. Let $\mathcal{D}(\Delta)$ be an algebra of abstract differential operators. For $z \in \mathbb{C}$, one defines the *complex powers* Δ^{-z} of Δ using functional calculus :

$$\Delta^{-z} = \frac{1}{2\pi i} \int \lambda^{-z} (\lambda - \Delta)^{-1} d\lambda$$

where the contour of integration is a vertical line pointing downwards separating 0 and the (discrete) spectrum of Δ . This converges in the operator norm when $\text{Re}(z) > 0$, and using the semi-group property, all the complex powers can be defined after multiplying by Δ^k , for $k \in \mathbb{N}$ large enough. Moreover, since Δ has compact resolvent, the complex powers of Δ are well defined operators on H^∞ .

We will suppose that there exists a $d \geq 0$ such that for every $X \in \mathcal{D}_q(\Delta)$, the operator $X\Delta^{-z}$ extends to a trace-class operator on H for z on the half-plane $\operatorname{Re}(z) > \frac{q+d}{r}$. The *zeta function* of X is

$$\zeta_X(z) = \operatorname{Tr}(X\Delta^{-z/r})$$

The smallest d verifying the above property is called the *analytic dimension* of $\mathcal{D}(\Delta)$. In this case, the zeta function is holomorphic on the half-plane $\operatorname{Re}(z) > q+d$. We shall say that $\mathcal{D}(\Delta)$ has the *analytic continuation property* if for every $X \in \mathcal{D}(\Delta)$, the associated zeta function extends to a meromorphic function of the whole complex plane.

These properties are set for all the section, unless if it is explicitly mentioned.

These notions come from properties of the zeta function on a closed Riemannian manifold M : it is well-known that the algebra of differential operators on M has analytic dimension $\dim M$ and the analytic continuation property. Its extension to a meromorphic function has at most simple poles at the integers smaller than $\dim M$. In the case where M is foliated, the dimension of the leaves appears in the analytic dimension when working in the suitable context. Hence, the zeta function provide informations not only on the topology of M , but also on its the geometric structure, illustrating the relevance of this abstraction.

1.4. Abstract Pseudodifferential Operators. Let $\mathcal{D}(\Delta)$ an algebra of abstract differential operators of analytic dimension d . To define the notion of pseudodifferential operators, we need a more general notion of order, not necessary integral, which covers the one induced by the filtration of $\mathcal{D}(\Delta)$.

DEFINITION 1.3. An operator $T : H^\infty \rightarrow H^\infty$ is said to have *pseudodifferential order* $m \in \mathbb{R}$ if for every $s \geq 0$, it extends to a bounded operator from H^{m+s} to H^s . In addition, we require that operators of analytic order strictly less than $-d$ are trace-class operators.

That this notion of order covers the differential order is due to the elliptic estimate, as already remarked in Section 1.1. The space of such operators, denoted $\operatorname{Op}(\Delta)$, forms a \mathbb{R} -filtered algebra. There is also a notion of regularizing operators which are, as expected, the elements of the (two-sided) ideal of operators of all order.

REMARK 1.4. Higson uses in [7] the term "analytic order", but as the examples we deal with in the paper are about pseudodifferential operators, we prefer the term pseudodifferential order.

EXAMPLE 1.5. For every $\lambda \in \mathbb{C}$ not contained in the spectrum of Δ , the resolvent $(\lambda - \Delta)^{-1}$ has analytic order r . Moreover, by spectral theory, its norm as an operator between Sobolev spaces is a $O(|\lambda|^{-1})$.

The following notion is due to Uuye, cf. [12]. We just added an assumption on the zeta function which is necessary for what we do.

DEFINITION 1.6. An algebra of abstract pseudodifferential operators is a \mathbb{R} -filtered subalgebra $\Psi(\Delta)$ of $\operatorname{Op}(\Delta)$, also denoted Ψ when the context is clear, satisfying

$$\Delta^{z/r}\Psi^m \subset \Psi^{\operatorname{Re}(z)+m}, \quad \Psi^m\Delta^{z/r} \subset \Psi^{\operatorname{Re}(z)+m}$$

and which commutes, up to operators of lower order, with the complex powers of $\Delta^{1/r}$, that is , for all $m \in \mathbb{R}$, $z \in \mathbb{C}$

$$[\Delta^{z/r}, \Psi^m] \subset \Psi^{\operatorname{Re}(z)+m-1}$$

Moreover, we suppose that for every $P \in \Psi^m(\Delta)$, the zeta function

$$\zeta_P(z) = \text{Tr}(P\Delta^{-z/r})$$

is holomorphic on the half-plane $\text{Re}(z) > m + d$, and extends to a meromorphic function of the whole complex plane. We shall denote by

$$\Psi^{-\infty} = \bigcap_{m \in \mathbb{R}} \Psi^m$$

Of course, this is true for the algebra of (classical) pseudodifferential operators on a closed manifold. We shall recall later what happens in the example of Heisenberg pseudodifferential calculus on a foliation, as described by Connes and Moscovici in [4].

We end this part with a notion of asymptotic expansion for abstract pseudodifferential operators. This can be seen as "convergence under the residue".

DEFINITION 1.7. Let T and T_α (α in a set A) be operators on Ψ . We shall write

$$T \sim \sum_{\alpha \in A} T_\alpha$$

if there exists $c > 0$ and a finite subset $F \subset A$ such that for all finite set $F' \subset A$ containing F , the map

$$z \mapsto \text{Tr} \left((T - \sum_{\alpha \in F'} T_\alpha) \Delta^{z/r} \right)$$

is holomorphic in a half-plane $\text{Re}(z) > -c$ (which contains $z = 0$).

EXAMPLE 1.8. Suppose that for every $M > 0$, there exists a finite subset $F \subset A$ such that

$$T - \sum_{\alpha \in F} T_\alpha \in \Psi^{-M}$$

Then, $T \sim \sum_{\alpha \in A} T_\alpha$

In this context, asymptotic means that when taking values under the residue, such infinite sums, which have no reason to converge in the operator norm, are in fact finite sums. Thus, this will allow us to disregard analytic subtleties and to consider these sums only as formal expansions without wondering if they converge or not. In other words, this notion allows to adopt an algebraic viewpoint. To this effect, the following lemma is crucial.

LEMMA 1.9. (Connes-Moscovici's trick, [4, 7]) *Let $Q \in \Psi(\Delta)$ be an abstract pseudodifferential operator. Then, for any $z \in \mathbb{C}$, we have*

$$(1.1) \quad [\Delta^{-z}, Q] \sim \sum_{k \geq 1} \binom{-z}{k} Q^{(k)} \Delta^{-z-k}$$

where we denote $Q^{(k)} = \text{ad}(\Delta)^k(Q)$, $\text{ad}(\Delta) = [\Delta, \cdot]$.

REMARK 1.10. The pseudodifferential order of terms in the sum decreases to $-\infty$, so that the difference between $[\Delta^{-z}, Q]$ and the sum becomes more and more regularizing as the number of terms grows.

PROOF. For $z \in \mathbb{C}$ of positive real part large enough, one proves, using Cauchy formulas and reasoning by induction, that the following identity holds (cf [7], Lemma 4.20) :

$$(1.2) \quad \Delta^{-z}Q - Q\Delta^{-z} = \sum_{k=1}^N \binom{-z}{k} Q^{(k)} \Delta^{-z-k} + \frac{1}{2\pi i} \int \lambda^{-z} (\lambda - \Delta)^{-1} Q^{(N+1)} (\lambda - \Delta)^{-N-1} d\lambda$$

By the elliptic estimate, the integral term in the right hand-side has pseudodifferential order $\text{ord}Q + (N+1)r - N - 1 - (N+2)r = \text{ord}(Q) - r - N - 1$, which can therefore be made as small as we want by taking N large. This proves the lemma in the case where $\text{Re}(z) > 0$. The general case follows from the analytic continuation property. \square

1.5. Higher traces on the algebra of abstract pseudodifferential operators. We give in this paragraph a simple generalization of the Wodzicki residue trace, when the zeta function of the algebra $\mathcal{D}(\Delta)$ has poles of arbitrary order. Actually, this was already noticed by Connes and Moscovici (see [4]).

PROPOSITION 1.11. *Let $\Psi(\Delta)$ an algebra of abstract pseudodifferential operators, following the context of the previous paragraphs. Suppose that the associated zeta function has a pole of order $p \geq 1$ in 0. Then, the functional*

$$\oint^p P = \text{Res}_{z=0} z^{p-1} \text{Tr}(P \Delta^{-z/r})$$

defines a trace on $\Psi(\Delta)$.

PROOF. Let $P, Q \in \Psi(\Delta)$. Then, for $\text{Re}(z) \gg 0$, we can use the trace property on commutators to write :

$$\text{Tr}([P, Q] \Delta^{-z/r}) = \text{Tr}(P(Q - \Delta^{-z/r} Q \Delta^{z/r}) \Delta^{-z/r})$$

Hence, using the analytic continuation property, we have

$$\oint^p [P, Q] = \text{Res}_{z=0} z^{p-1} \text{Tr}(P(Q - \Delta^{-z/r} Q \Delta^{z/r}) \Delta^{-z/r})$$

By Lemma 1.9,

$$\Delta^{-z/r} Q - Q \Delta^{-z/r} \sim \sum_{k \geq 1} \binom{-z/r}{k} Q^{(k)} \Delta^{-k} \cdot \Delta^{-z/r}$$

so that,

$$\oint^p [P, Q] = \text{Res}_{z=0} \sum_{k \geq 1} z^{p-1} \text{Tr} \left(\binom{-z/r}{k} Q^{(k)} \Delta^{-k} \cdot \Delta^{-z/r} \right)$$

The sum is finite : Indeed, the order of $Q^{(k)} \Delta^{-k}$ is $\text{ord}(Q) - k$, so the terms in the sum above become holomorphic at $z = 0$ when k is large enough, and vanish when taking values under the residue. Finally, the finite sum remaining vanishes since the zeta function has at most a pole of order p at 0. \square

If $0 \leq k < p$, then \oint^k is no more a trace in general, but one has an explicit relation expressing the commutators, cf. [4].

1.6. The example of Connes and Moscovici.

1.6.1. *Heisenberg pseudodifferential calculus on foliations.* Let M be a foliated manifold of dimension n , and let \mathcal{F} be the integrable sub-bundle of the tangent bundle TM of M which defines the foliation. We denote the dimension of the leaves by p , and by $q = n - p$ their codimension.

For the moment, we work in distinguished local charts. Let (x_1, \dots, x_n) a distinguished local coordinate system of M , i.e, the vector fields $\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_p}$ (locally) span \mathcal{F} , so that $\frac{\partial}{\partial x_{p+1}}, \dots, \frac{\partial}{\partial x_n}$ are transverse to the leaves of the foliation. Connes and Moscovici constructed in [4] an algebra of generalized differential operators using Heisenberg calculus, whose main idea is that :

- The vector fields $\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_p}$ are of order 1.
- The vector fields $\frac{\partial}{\partial x_{p+1}}, \dots, \frac{\partial}{\partial x_n}$ are of order 2.

The Heisenberg pseudodifferential calculus consists in defining a class of smooth symbols $\sigma(x, \xi)$ on $\mathbb{R}_x^n \times \mathbb{R}_\xi^n$ which takes this notion of order into account. To this end, they set

$$|\xi'| = (\xi_1^4 + \dots + \xi_p^4 + \xi_{p+1}^2 + \dots + \xi_n^2)^{1/4}$$

$$\langle \alpha \rangle = \alpha_1 + \dots + \alpha_p + 2\alpha_{p+1} + \dots + 2\alpha_n$$

for every $\xi \in \mathbb{R}^n$, $\alpha \in \mathbb{N}^n$.

DEFINITION 1.12. A smooth function $\sigma(x, \xi) \in C^\infty(\mathbb{R}_x^n \times \mathbb{R}_\xi^n)$ is a Heisenberg symbol of order $m \in \mathbb{R}$ if σ is x -compactly supported, and if for every multi-index α, β , one has the following estimate

$$|\partial_x^\beta \partial_\xi^\alpha \sigma(x, \xi)| \leq (1 + |\xi'|)^{m - \langle \alpha \rangle}$$

To such a symbol σ of order m , one associates its left-quantization, which is the following operator

$$P : C^\infty(\mathbb{R}^n) \longrightarrow C^\infty(\mathbb{R}^n), \quad Pf(x) = \frac{1}{(2\pi)^n} \int_{\mathbb{R}^n} e^{ix \cdot \xi} \sigma(x, \xi) \hat{f}(\xi) d\xi$$

where \hat{f} denotes the Fourier transform of f . We shall say that P is a *Heisenberg pseudodifferential operator of order m* , and denote the class of such operators by $\Psi_H^m(\mathbb{R}^n)$. The Heisenberg regularizing operators, whose class is denoted by $\Psi^{-\infty}(\mathbb{R}^n)$, are those of arbitrary order, namely

$$\Psi^{-\infty}(\mathbb{R}^n) = \bigcap_{m \in \mathbb{R}} \Psi_H^m(\mathbb{R}^n)$$

The reason why there is no H -subscript is that the Heisenberg regularizing operators are exactly the regularizing operators of the usual pseudodifferential calculus, i.e the operators with smooth Schwartz kernel.

Actually we shall restrict to the smaller class of *classical Heisenberg pseudodifferential operators*. For this, we first define the *Heisenberg dilations*

$$\lambda \cdot (\xi_1, \dots, \xi_p, \xi_{p+1}, \dots, \xi_n) = (\lambda \xi_1, \dots, \lambda \xi_p, \lambda^2 \xi_{p+1}, \dots, \lambda^2 \xi_n)$$

for any non-zero $\lambda \in \mathbb{R}$ and non-zero $\xi \in \mathbb{R}^n$.

Then, a Heisenberg pseudodifferential operator $P \in \Psi_H^m(\mathbb{R}^n)$ of order m is said *classical* if its symbol σ has an asymptotic expansion

$$(1.3) \quad \sigma(x, \xi) \sim \sum_{j \geq 0} \sigma_{m-j}(x, \xi)$$

where $\sigma_{m-j}(x, \xi) \in S_H^{m-j}(\mathbb{R}^n)$ are *Heisenberg homogeneous*, that is, for any non-zero $\lambda \in \mathbb{R}$,

$$\sigma_{m-j}(x, \lambda \cdot \xi) = \lambda^{m-j} \sigma_{m-j}(x, \xi)$$

The \sim means that for every $M > 0$, there exists an integer N such that $\sigma - \sum_{j=0}^N \sigma_{m-j} \in \mathcal{S}_H^{-M}(\mathbb{R}^n)$. To avoid an overweight of notations, we shall keep the notation Ψ_H to refer to classical elements.

Another important point is the behaviour of symbols towards composition of classical pseudodifferential operators. Of course, if $P, Q \in \Psi_H(\mathbb{R}^n)$ are Heisenberg pseudodifferential operators of symbols σ_P and σ_Q , PQ is also a Heisenberg pseudodifferential operator of order at most $\text{ord}(P) + \text{ord}(Q)$, and its the symbol σ_{PQ} is given by the following asymptotic expansion called the *star-product* of symbols, given by the formula

$$(1.4) \quad \sigma_{PQ}(x, \xi) = \sigma_P \star \sigma_Q(x, \xi) \sim \sum_{|\alpha| \geq 0} \frac{(-\mathbf{i})^{|\alpha|}}{\alpha!} \partial_\xi^\alpha \sigma_P(x, \xi) \partial_x^\alpha \sigma_Q(x, \xi)$$

Note that the order of each symbol in the sum is decreasing while $|\alpha|$ is increasing.

We define the *algebra of Heisenberg formal classical symbols* $\mathcal{S}_H(\mathbb{R}^n)$ as the quotient

$$\mathcal{S}_H(\mathbb{R}^n) = \Psi_H(\mathbb{R}^n) / \Psi^{-\infty}(\mathbb{R}^n)$$

Its elements are formal sums given in (1.3), and the product is the star product (1.4). Note that the \sim can be replaced by equalities when working at a formal level.

We now deal with ellipticity in this context. A Heisenberg pseudodifferential operator is said *Heisenberg elliptic* if it is invertible in the unitalization $\mathcal{S}_H(\mathbb{R}^n)^+$ of $\mathcal{S}_H(\mathbb{R}^n)$. One can show that this is actually equivalent to say that its *Heisenberg principal symbol*, i.e the symbol of higher degree in the expansion (1.3) is invertible on $\mathbb{R}_x^n \times \mathbb{R}_\xi^n \setminus \{0\}$. An adaptation of arguments from classical elliptic regularity shows that the elliptic estimate holds in this case. A remarkable specificity of these operators is that they are hypoelliptic, but not elliptic in general. Nevertheless, they remain Fredholm operators between Sobolev spaces relative to this context. The interested reader should consult [1] for details.

EXAMPLE 1.13. The following operator, also called sub-elliptic sub-laplacian,

$$\Delta_H = \partial_{x_1}^4 + \dots + \partial_{x_p}^4 - (\partial_{x_{p+1}}^2 + \dots + \partial_{x_n}^2)$$

has Heisenberg principal symbol $\sigma(x, \xi) = |\xi|'^4$, and is therefore Heisenberg elliptic. However, its usual principal symbol, as an ordinary differential operator, is $(x, \xi) \mapsto \sum_{i=1}^p \xi_i^4$, so Δ_H is clearly not elliptic.

Finally, Heisenberg pseudodifferential operators behave well towards distinguished charts change. Therefore, Heisenberg pseudodifferential calculus can be defined globally on foliations by using a partition of unity. Then, for a foliated manifold M , we denote by $\Psi_H^m(M)$ the algebra of Heisenberg pseudodifferential operators on M .

It is not very difficult to verify the required assumptions of Definition 1.6. However, what concerns the zeta function is not obvious.

1.6.2. Residue Trace on Foliations. We now recall these results, proved by Connes and Moscovici in [4].

THEOREM 1.14. (Connes-Moscovici, [4]) *Let M be a foliated manifold of dimension n , p be the dimensions of the leaves, and $P \in \Psi^m(M)$ be a Heisenberg pseudodifferential operator of order $m \in \mathbb{R}$. Let Δ the sub-elliptic sub-laplacian defined in Example 1.13, that we extend globally to M by using a partition of unity. Then, the zeta function*

$$\zeta_P(z) = \text{Tr}(P\Delta^{-z/4})$$

is holomorphic on the half-plane $\operatorname{Re}(z) > m + p + 2q$, and extends to a meromorphic function of the whole complex plane, with at most simple poles in the set

$$\{m + p + 2q, m + p + 2q - 1, \dots\}$$

REMARK 1.15. The analytic dimension of the algebra of Heisenberg differential operators is then $p + 2q$. Note that we thus recover the dimension of the leaves of the foliation, and that the "2" is the degree of the transverse vector fields.

The meromorphic extension of the zeta function given by this theorem allows the construction of a Wodzicki-Guillemin trace on $\mathcal{S}_H(M) = \Psi_H(M)/\Psi^{-\infty}(M)$.

THEOREM 1.16. (Connes-Moscovici, [4]) *The Wodzicki residue functional*

$$\int : \mathcal{S}_H(M) \longrightarrow \mathbb{C}, \quad P \longmapsto \operatorname{Res}_{z=0} \operatorname{Tr}(P\Delta^{-z/4})$$

is a trace. It is the unique trace on $\mathcal{S}_H(M)$, up to a multiplicative constant. Moreover, for $P \in \Psi_H(M)$, we have the following formula, only depending on the symbol σ of P .

$$(1.5) \quad \int P = \frac{1}{(2\pi)^n} \int_{S_H^*M} \iota_L \left(\sigma_{-(p+2q)}(x, \xi) \frac{\omega^n}{n!} \right)$$

Here, S_H^*M is the Heisenberg cosphere bundle, that is, the sub-bundle

$$S_H^*M = \{(x, \xi) \in T^*M; |\xi|' = 1\}$$

L is the generator of the Heisenberg dilations, ι stands for the interior product and ω denotes the standard symplectic form on T^*M .

REMARK 1.17. All these results still holds for Heisenberg pseudodifferential operators acting on sections of a vector bundle E over M : In this case, the symbol $\sigma_{-(p+2q)}(x, \xi)$ above is at each point (x, ξ) an endomorphism acting on the fibre E_x , and (1.5) becomes:

$$\int P = \frac{1}{(2\pi)^n} \int_{S_H^*M} \iota_L \left(\operatorname{tr}(\sigma_{-(p+2q)}(x, \xi)) \frac{\omega^n}{n!} \right)$$

where tr denotes the trace of endomorphisms.

2. THE RADUL COCYCLE FOR ABSTRACT PSEUDODIFFERENTIAL OPERATORS

2.1. **Extensions and index theorems.** We begin with another abstract setting. Let A be an associative algebra over \mathbb{C} , possibly without unit, and I an ideal in A . The extension

$$0 \longrightarrow I \longrightarrow A \longrightarrow A/I \longrightarrow 0$$

gives rise to the following diagram, relating the index map in algebraic K-theory and excision in periodic cyclic homology

$$(2.1) \quad \begin{array}{ccc} K_1^{\operatorname{alg}}(A/I) & \xrightarrow{\operatorname{Ind}} & K_0^{\operatorname{alg}}(I) \\ \downarrow \operatorname{ch}_1 & & \downarrow \operatorname{ch}_0 \\ \operatorname{HP}_1(A/I) & \xrightarrow{\partial} & \operatorname{HP}_0(I) \end{array}$$

The vertical arrows are respectively the odd and even Chern character. Nistor shows in [8] that this diagram is commutative. Then, if we denote again $\partial : \operatorname{HP}^0(I) \rightarrow \operatorname{HP}^1(A/I)$ the excision map in cohomology, the following equality holds,

$$(2.2) \quad \langle [\tau], \operatorname{ch}_0 \operatorname{Ind}[u] \rangle = \langle \partial[\tau], \operatorname{ch}_1[u] \rangle$$

for every $[\tau] \in \text{HP}^0(I)$ and every $[u] \in K_1(A/I)$. One should have in mind that the left hand-side is an "analytic index", and think about the right hand-side as a "topological index".

Let us recall the construction of a boundary map ∂ in cohomology in a useful particular case, drawn from [8]. Let $[\tau] \in \text{HP}^0(I)$ be given by a hypertrace $\tau : I \rightarrow \mathbb{C}$, i.e a linear map satisfying the condition $\tau([A, I]) = 0$, then let us recall how to compute $\partial[\tau] \in \text{HP}^1(A/I)$. To begin, choose a lift $\tilde{\tau} : A \rightarrow \mathbb{C}$ of τ , such that $\tilde{\tau}$ is linear (in general, this is not a trace), and a linear section $\sigma : A/I \rightarrow A$ such that $\sigma(1) = 1$, after adjoining a unit where we have to. Then, $\partial[\tau]$ is represented by the following cyclic cocycle :

$$c(a_0, a_1) = b\tilde{\tau}(\sigma(a_0), \sigma(a_1)) = \tilde{\tau}([\sigma(a_0), \sigma(a_1)])$$

where b is the Hochschild coboundary recalled in Section 3.1.

2.2. The generalized Radul cocycle. We can finally come to the main theorem of this section. Let $\mathcal{D}(\Delta)$ be an algebra of abstract differential operators and $\Psi = \Psi(\Delta)$ be an algebra of abstract pseudodifferential operators. We consider the extension

$$0 \longrightarrow \Psi^{-\infty} \longrightarrow \Psi \longrightarrow \mathcal{S} \longrightarrow 0$$

where \mathcal{S} is the quotient $\Psi/\Psi^{-\infty}$. The operator trace on $\Psi^{-\infty}$ is well defined, hence it defines a periodic cyclic cohomology class $[\text{Tr}] \in \text{HP}^0(\Psi^{-\infty})$. It also satisfies $\text{Tr}([\Psi^{-\infty}, \Psi]) = 0$. In addition, let $\partial : \text{HP}^0(\Psi^{-\infty}) \rightarrow \text{HP}^1(\mathcal{S})$ denote the excision map in periodic cyclic cohomology associated to the above extension.

THEOREM 2.1. *Suppose that the pole at zero of the zeta function is of order $p \geq 1$. Then, the class $\partial[\text{Tr}] \in \text{HP}^1(\mathcal{S})$ is represented by the following cyclic 1-cocycle :*

$$c(a_0, a_1) = \int a_0 \delta(a_1) - \frac{1}{2!} \int a_0 \delta^2(a_1) + \dots + \frac{(-1)^{p-1}}{p!} \int a_0 \delta^p(a_1)$$

where $\delta(a) = [\log \Delta^{1/r}, a]$ and $\delta^k(a) = \delta^{k-1}(\delta(a))$ is defined by induction. We shall call this cocycle the (generalized) Radul cocycle.

Here, the commutator $[\log \Delta^{1/r}, a]$ is defined as the non-convergent asymptotic expansion

$$(2.3) \quad [\log \Delta^{1/r}, a] \sim \frac{1}{r} \sum_{k \geq 1} \frac{(-1)^{k-1}}{k} a^{(k)} \Delta^{-k}$$

where $a^{(k)}$ has the same meaning as in Lemma 1.9. This expansion arises by first using functional calculus :

$$\log \Delta^{1/r} = \frac{1}{2\pi i} \int \log \lambda^{1/r} (\lambda - \Delta)^{-1} d\lambda$$

and then, reproducing the same calculations made in the proof of Lemma 1.9 to obtain the formula (cf. [7] for details). In particular, note that $\log \Delta^{1/r} = \frac{1}{r} \log \Delta$.

Another equivalent expansion possible, that we will also use, is the following

$$(2.4) \quad [\log \Delta^{1/r}, a] \sim \sum_{k \geq 1} \frac{(-1)^{k-1}}{k} a^{[k]} \Delta^{-k/r}$$

where $a^{[1]} = [\Delta^{1/r}, a]$, and $a^{[k+1]} = [\Delta^{1/r}, a^{[k]}]$.

Before proving the result, let us give a heuristic explanation of how to get this formula. We first lift the trace on $\Psi^{-\infty}$ to a linear map $\tilde{\tau}$ on Ψ using a zeta function regularization by "Partie Finie",

$$\tilde{\tau}(P) = \text{Pf}_{z=0} \text{Tr}(P \Delta^{-z/r})$$

for any $P \in \Psi$. The "Partie Finie" Pf is defined as the constant term in the Laurent expansion of a meromorphic function. Let $Q \in \Psi$ be another pseudodifferential operator. Then, we have

$$\text{Pf}_{z=0} \text{Tr}([P, Q] \Delta^{-z/r}) = \text{Res}_{z=0} \text{Tr} \left(P \cdot \frac{Q - \Delta^{-z/r} Q \Delta^{z/r}}{z} \Delta^{-z/r} \right)$$

by reasoning first for $z \in \mathbb{C}$ of sufficiently large real part to use the trace property, and then applying the analytic continuation property. Then, informally we can think of the complex powers of Δ as

$$\Delta^{z/r} = e^{\log \Delta \cdot z/r} = 1 + \frac{z}{r} \log \Delta + \dots + \frac{1}{p!} \left(\frac{z}{r} \right)^p (\log \Delta)^p + O(z^{p+1})$$

which after some calculations, gives the expansion

$$(Q - \Delta^{-z/r} Q \Delta^{z/r}) \Delta^{-z/r} = z \delta(Q) - \frac{z^2}{2} \delta^2(Q) + \dots + (-1)^{p-1} \frac{z^p}{p!} \delta^p(Q) + O(z^{p+1})$$

PROOF. Let $P, Q \in \Psi$ be two abstract pseudodifferential operators. The beginning of the proof is the same as the heuristic argument given above, so we start from the equality

$$\begin{aligned} \text{Pf}_{z=0} \text{Tr}([P, Q] \Delta^{-z/r}) &= \text{Res}_{z=0} \text{Tr} \left(P \cdot \frac{Q - \Delta^{-z/r} Q \Delta^{z/r}}{z} \Delta^{-z/r} \right) \\ &= \text{Res}_{z=0} \text{Tr} \left(P \cdot \frac{1}{z} \sum_{k \geq 1} \binom{-z/r}{k} Q^{(k)} \Delta^{-k} \cdot \Delta^{-z/r} \right) \end{aligned}$$

The second equality comes from Lemma 1.9.

Then, let X be an indeterminate. As power series over the complex numbers with indeterminate X , we remark that for any $z \in \mathbb{C}$, one has

$$\frac{1}{z} \sum_{k \geq 1} \binom{-z/r}{k} X^k = \frac{1}{z} ((1+X)^{-z/r} - 1)$$

On the other hand, we have, for $q \in \mathbb{N}$,

$$\text{ad}(\log \Delta^{1/r})^q(Q) = \frac{1}{r^q} [\log \Delta, [\dots, [\log \Delta, Q]]] \sim \frac{1}{r^q} \sum_{k \geq q} \sum_{k_1 + \dots + k_q = k} \frac{(-1)^{k-q}}{k_1 \dots k_q} Q^{(k)} \Delta^{-k}$$

Using once more the indeterminate X , one has

$$\begin{aligned} \sum_{k \geq q} \sum_{k_1 + \dots + k_q = k} \frac{(-1)^{k-q}}{k_1 \dots k_q} X^k &= \left(\sum_{l \geq 1} \frac{(-1)^{l-1} X^l}{l} \right)^q \\ &= \log(1+X)^q \end{aligned}$$

thus obtaining

$$\sum_{q \geq 1} \frac{(-1)^{q-1}}{q!} \frac{z^{q-1}}{r^q} \log(1+X)^q = \frac{1}{z} ((1+X)^{-z/r} - 1)$$

This proves that the coefficients of $Q^{(k)} \Delta^{-k}$ in the sums

$$\frac{1}{z} \sum_{k \geq 1} \binom{-z}{k} Q^{(k)} \Delta^{-k}, \quad \sum_{q \geq 1} \frac{(-1)^{q-1}}{q!} \frac{z^{q-1}}{r^q} \left(\sum_{k \geq q} \sum_{k_1 + \dots + k_q = k} \frac{(-1)^{k-q}}{k_1 \dots k_q} Q^{(k)} \Delta^{-k} \right)$$

are the same, hence the result follows. \square

Applying the pairing (2.2), we have an index formula.

EXAMPLE 2.2. Let M be a closed foliated manifold with integrable sub-bundle $F \in TM$, Δ the sub-elliptic sub-laplacian of Example 1.13 and take $\Psi(\Delta) = \Psi_H(M)$ the algebra of (classical) Heisenberg pseudodifferential operators on M , $\Psi^{-\infty}(\Delta) = \Psi^{-\infty}(M)$ the ideal of regularizing operators. The quotient $\Psi/\Psi^{-\infty}$ is the algebra $\mathcal{S}_H(M)$ of classical Heisenberg formal symbols. A trace on $\Psi^{-\infty}(M)$ is given by

$$(2.5) \quad \tau(K) = \text{Tr}(K) = \int_{\mathcal{M}} k(x, x) d\text{vol}(x)$$

where k is the Schwartz kernel of K . Then, using the residue defined in Theorem 1.16 and applying Theorem 2.1, $\partial[\tau]$ is represented by the following cyclic 1-cocycle on $\mathcal{S}_H(M)$:

$$(2.6) \quad c(a_0, a_1) = \oint a_0[\log|\xi|', a_1]$$

With a slight abuse of notation, we put the symbol $\log|\xi|'$ instead of the operator $\log\Delta^{1/4}$. We emphasize that the product of symbols is the star-product defined in (1.4), but we omit the notation \star .

Remark that $\log|\xi|'$ is a log-polyhomogeneous (Heisenberg) symbol and is not classical, but from (2.4), it is clear that its commutator with any element of $\mathcal{S}_H(M)$ is. Note also that the cocycle is defined on the symbols rather than on the operators, but this does not matter since the Connes-Moscovici residue kills the smoothing contributions. In particular, only a finite number of terms of the star-product are involved.

From this cocycle, we then get an index formula for Heisenberg elliptic pseudodifferential operators. Indeed, if P is such an operator of formal symbol $u \in \mathcal{S}_H(M)$, and Q a parametrix of P in the Heisenberg calculus of formal symbol $u^{-1} \in \mathcal{S}_H(M)$, then, the Fredholm index of P is given by

$$\text{Ind}(P) = c(u^{-1}, u)$$

As the Radul cocycle is given by a Wodzicki residue, it is local in the sense of Connes-Moscovici. However, it seems to be an unattainable task to get a topological index formula in terms of the principal symbol since by (1.5), we have to compute the symbol of order $-(p+2q)$ of $u^{-1}[\log|\xi|', u]$. At first sight, many terms of the formal expansions of u and u^{-1} , as well as many of their higher derivatives, seem to be involved. We shall see in next section a way to overcome this difficulty.

3. A COMPUTATION OF THE RADUL COCYCLE

This section is devoted to show how one may recover interesting index formulas from the Radul cocycle, working on the simplest foliation possible. For all this section, even if it is not explicitly mentioned, we consider \mathbb{R}^n as a trivial foliation $\mathbb{R}^p \times \mathbb{R}^q$, where $0 \leq p \leq n$ and $q = n - p$, and consider the associated classical Heisenberg pseudodifferential operators $\Psi_H^0(\mathbb{R}^n)$ of order 0.

Our goal is to show that the Radul cocycle (2.6) on $\mathcal{S}_H^0(\mathbb{R}^n)$ is cohomologous in $HP^1(\mathcal{S}_H(\mathbb{R}^n))$ to simple inhomogeneous (B, b) -cocycles of higher degree, making the computation of the index problem easier. We shall always use coordinates adapted to the foliation $\mathbb{R}^p \times \mathbb{R}^q$.

We shall give two constructions but before, we briefly recall how to define the (B, b) -bicomplex.

3.1. **The (B, b) -bicomplex.** Let A be an associative algebra over \mathbb{C} . For $k \geq 0$, denote by $CC^k(A)$ the space of $(k+1)$ -linear forms on the unitalization A^+ of A such that $\phi(a_0, \dots, a_k) = 0$ when $a_i = 1$ for some $i \geq 1$. Then, define the differentials

$$B : CC^{k+1}(A) \longrightarrow CC^k(A), \quad b : CC^k(A) \longrightarrow CC^{k+1}(A)$$

by the formulas

$$\begin{aligned} B\phi(a_0, \dots, a_k) &= \sum_{i=0}^k (-1)^{ik} \phi(1, a_i, \dots, a_k, a_0, \dots, a_{i-1}) \\ b\phi(a_0, \dots, a_{k+1}) &= \sum_{i=0}^k (-1)^i \phi(a_0, \dots, a_{i-1}, a_i a_{i+1}, a_{i+2}, \dots, a_{k+1}) \\ &\quad + (-1)^{k+1} \phi(a_{k+1} a_0, \dots, a_k) \end{aligned}$$

that is, $B^2 = b^2 = 0$. Moreover, B and b anticommute, which allows to define the (B, b) -bicomplex

$$\begin{array}{ccccc} & & \vdots & & \vdots & & \vdots \\ & & \uparrow b & & \uparrow b & & \uparrow b \\ \dots & \xrightarrow{B} & CC^2(A) & \xrightarrow{B} & CC^1(A) & \xrightarrow{B} & CC^0(A) \\ & & \uparrow b & & \uparrow b & & \\ \dots & \xrightarrow{B} & CC^1(A) & \xrightarrow{B} & CC^0(A) & & \\ & & \uparrow b & & & & \\ \dots & \xrightarrow{B} & CC^0(A) & & & & \end{array}$$

Then, the periodic cyclic cohomology $HP^\bullet(A)$ is the cohomology of the total complex. More precisely, it is the cohomology of the 2-periodic complex

$$\dots \xrightarrow{B+b} CC^{\text{even}}(A) \xrightarrow{B+b} CC^{\text{odd}}(A) \xrightarrow{B+b} CC^{\text{even}}(A) \xrightarrow{B+b} \dots$$

where

$$\begin{aligned} CC^{\text{even}}(A) &= CC^0(A) \oplus CC^2(A) \oplus \dots \\ CC^{\text{odd}}(A) &= CC^1(A) \oplus CC^3(A) \oplus \dots \end{aligned}$$

Hence, there are only an even and an odd periodic cyclic cohomology groups, respectively denoted $HP^0(A)$ and $HP^1(A)$.

REMARK 3.1. Sometimes, authors consider the total differential $B - b$ instead of $B + b$.

3.2. General context. Recall from Section 1.5 that the residue trace of a Heisenberg pseudodifferential operator $P \in \Psi_H(\mathbb{R}^n)$ of symbol σ is given by

$$(3.1) \quad \int P = \frac{1}{(2\pi)^n} \int_{S_H^* \mathbb{R}^n} \iota_L \left(\sigma_{-(p+2q)}(x, \xi) \frac{\omega^n}{n!} \right)$$

where $\sigma_{-(p+2q)}$ is the Heisenberg homogeneous term of order $-(p+2q)$ in the asymptotic expansion of σ , $\omega = \sum_i dx_i d\xi_i$ is the standard symplectic form on $T^*\mathbb{R}^n = \mathbb{R}_x^n \times \mathbb{R}_\xi^n$, and L is the generator of the Heisenberg dilations, given by the formula

$$L = \sum_{i=1}^p \xi_i \partial_{\xi_i} + 2 \sum_{i=p+1}^n \xi_i \partial_{\xi_i}$$

Note that in this example, the sub-elliptic sub-laplacian does not have a compact resolvent since we work on \mathbb{R}^n . However, the results in Section 1.6.2 on the Wodzicki residue still holds because we consider pseudodifferential operators which have compact support.

We first extend the trace on $\Psi^{-\infty}(\mathbb{R}^n)$ given in (2.5) to a graded trace on the graded algebra $\Psi^{-\infty}(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$, using a Berezin integral :

$$\mathrm{Tr}(K \otimes \alpha) = \alpha_{[2n]} \mathrm{Tr}(K)$$

where $K \in \Psi^{-\infty}(\mathbb{R}^n)$, and $\alpha_{[2n]}$ is the coefficient of the form $dx_1 \dots dx_n d\xi_1 \dots d\xi_n$ in α (the wedges are dropped to simplify notations). Here, we emphasize once more that $T^*\mathbb{R}^n$ is seen as the vector space $\mathbb{R}_x^n \times \mathbb{R}_\xi^n$. Therefore $\Lambda^\bullet T^*\mathbb{R}^n$ stands for the exterior algebra of the vector space $T^*\mathbb{R}^n = \mathbb{R}_x^n \times \mathbb{R}_\xi^n$, and not for the vector bundle of exterior powers of the cotangent bundle, as usual.

Moreover, the Wodzicki residue trace on $\Psi_H(\mathbb{R}^n)$ is given by a zeta function regularization of this trace. Therefore, the latter procedure also extends the Wodzicki residue trace to a graded trace on the graded algebra $\Psi_H(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$. The latter descends to a graded trace on $\mathcal{S}_H(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$. The composition law of pseudodifferential operators, or the star-product of symbols for the latter, are extended to these algebras just by imposing that they commute to elements of the exterior algebra.

Remark also that the following commutation relations hold

$$[x_i, \xi_j] = i\delta_{i,j}, \quad [x_i, x_j] = [\xi_i, \xi_j] = 0$$

where we denote $i = \sqrt{-1}$. In short, $\mathrm{ad}(x_i)$ and $\mathrm{ad}(\xi_i)$ are respectively the differentiation of symbols with respect to the variables ξ_i and x_i .

Finally, let F be the multiplier on $\mathcal{S}_H(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$ defined by

$$F = \sum_i (x_i d\xi_i + \xi_i dx_i)$$

As the two following lemmas might indicate, this operator will play a role rather similar to operators usually denoted by F when dealing with finitely summable Fredholm modules. The difference is that this F here is not the main object of study, and acts more as an intermediate towards the main result.

LEMMA 3.2. F^2 is equal to $i\omega$, where ω is the standard symplectic form on $T^*\mathbb{R}^n$. In particular, F^2 commutes to every element in $\mathcal{S}_H(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$.

LEMMA 3.3. For every symbol $a \in \mathcal{S}_H(\mathbb{R}^n)$, one has

$$[F, a] = ida = i \sum_i \left(\frac{\partial a}{\partial x_i} dx_i + \frac{\partial a}{\partial \xi_i} d\xi_i \right)$$

The proof of both lemmas follows from a simple computation, just using the commutation relations mentioned above. Another important property of the multiplier F , easy to verify, is the following

LEMMA 3.4. For every $a \in \mathcal{S}_H(\mathbb{R}^n) \otimes \Lambda^\bullet T^*\mathbb{R}^n$, we have

$$\oint [F, a] = 0$$

3.3. Construction by excision. The previous lemma shows that it may be relevant to consider the following cyclic cocycles on $\Psi^{-\infty}(\mathbb{R}^n)$, inspired of Connes' cyclic cocycles associated to Fredholm modules (see [2] or [3]).

$$(3.2) \quad \phi_{2k}(a_0, \dots, a_{2k}) = \frac{k!}{i^k (2k)!} \mathrm{Tr} \left(a_0 [F, a_1] \dots [F, a_{2k}] \otimes \frac{\omega^{n-k}}{n!} \right)$$

for $0 \leq k \leq n$. Therefore, we obtain the following result, very similar to that of Connes.

PROPOSITION 3.5. *The periodic cyclic cohomology classes of the cyclic cocycles ϕ_{2k} are independent of k .*

PROOF. Set

$$(3.3) \quad \gamma_{2k+1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) = \frac{(k+1)!}{i^{k+1}(2k+2)!} \text{Tr} \left(\mathbf{a}_0 [F, \mathbf{a}_1] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k}}{n!} \right)$$

It is then a straightforward calculation to verify that $(B+b)\gamma_{2k+1} = \phi_{2k} - \phi_{2k+2}$, which shows the result. \square

At this stage, we are not very far from being done. To obtain the desired cyclic cocycles on the algebra $S_{\mathbb{H}}^0 \mathbb{R}^n \otimes \Lambda^* T^* \mathbb{R}^n$ from those previously constructed, it suffices to push the latter using excision in periodic cyclic cohomology. Indeed, as we have the pseudodifferential extension

$$0 \longrightarrow \Psi^{-\infty}(\mathbb{R}^n) \longrightarrow \Psi_{\mathbb{H}}^0(\mathbb{R}^n) \longrightarrow S_{\mathbb{H}}^0 \mathbb{R}^n \longrightarrow 0$$

we look at the image of the (B, b) -cocycles ϕ_{2k} under the boundary map

$$\partial : \text{HP}^0(\Psi^{-\infty}(\mathbb{R}^n)) \longrightarrow \text{HP}^1(S_{\mathbb{H}}^0 \mathbb{R}^n)$$

Thanks to this, the cocycles (3.2) involving the operator trace, which are highly non local, will be avoided and transferred to cocycles involving the Wodzicki residue.

To compute the image of the cocycles (3.2) under the excision map ∂ , a slight refinement of the techniques sketched in Sections 2.1 and 2.2 is required. We first lift the cocycles ϕ_{2k} on $\Psi^{-\infty}(\mathbb{R}^n)$ to cyclic cochains $\tilde{\phi}_{2k} \in \text{CC}^\bullet(\Psi_{\mathbb{H}}^0(\mathbb{R}^n))$ using a zeta function regularization,

$$\begin{aligned} \tilde{\phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k}) \\ = \frac{k!}{i^k(2k)!} \frac{1}{2k+1} \sum_{i=0}^{2k} \text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0 [F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] \Delta^{-z/4} [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

For $k=0$, we already know that $\partial[\phi_0]$ is represented by the Radul cocycle

$$c(\mathbf{a}_0, \mathbf{a}_1) = \int \mathbf{a}_0 \delta \mathbf{a}_1$$

where $\delta \mathbf{a}_1 = [\log |\xi|', \mathbf{a}_1]$.

Now, let $k \in \mathbb{N}$. Then, the usual construction of the boundary map in cohomology associated to an extension gives that $\partial[\phi_{2k}]$ is represented by the inhomogeneous (B, b) -cocycle

$$(B+b)\tilde{\phi}_{2k} = \psi_{2k-1} + \phi_{2k+1} \in \text{CC}^{2k-1}(\Psi_{\mathbb{H}}^0(\mathbb{R}^n)) \oplus \text{CC}^{2k+1}(\Psi_{\mathbb{H}}^0(\mathbb{R}^n))$$

where $\psi_{2k-1} = B\tilde{\phi}_{2k}$ and $\phi_{2k+1} = b\tilde{\phi}_{2k}$ are given by

$$(3.4) \quad \begin{aligned} \psi_{2k-1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \\ = \frac{k!}{i^k(2k)!} \sum_{i=0}^{2k-1} (-1)^{i+1} \int \left(\mathbf{a}_0 [F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] \delta F [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k-1}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

$$(3.5) \quad \begin{aligned} \phi_{2k+1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) \\ = \frac{k!}{i^k(2k+1)!} \sum_{i=1}^{2k+1} (-1)^{i-1} \int \left(\mathbf{a}_0 [F, \mathbf{a}_1] \dots [F, \mathbf{a}_{i-1}] \delta \mathbf{a}_i [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

where we define ψ_{-1} as zero. ϕ_1 is precisely the Radul cocycle. For the clarity of the exposition, the calculations will be detailed later in Appendix A. Then, we have :

PROPOSITION 3.6. *The Radul cocycle c is cohomologous in the (B, b) -complex, to the (B, b) -cocycles $(\psi_{2k-1}, \phi_{2k+1})$, for all $1 \leq k \leq n$.*

Indeed, usual properties of boundary maps in cohomology automatically ensures this result. As a matter of fact, one can be more precise and give explicitly the transgression cochains allowing to pass from one cocycle to another. For this, we lift the transgression cochain γ given in (3.3) to the (B, b) -cochain $\tilde{\gamma} \in CC^\bullet(\Psi_H(\mathbb{R}^n))$, using the same trick as before :

$$\begin{aligned} \tilde{\gamma}_{2k+1} = & \frac{(k+1)!}{i^{k+1}(2k+2)!} \frac{1}{2k+3} \left[\text{Pf}_{z=0} \text{Tr} \left(a_0 \Delta^{-z/4} F[a_1] \dots [F, a_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right. \\ & \left. + \sum_{i=0}^{2k+1} \text{Pf}_{z=0} \text{Tr} (a_0 F[a_1] \dots [F, a_i] \Delta^{-z/4} [F, a_{i+1}] \dots [F, a_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!}) \right] \end{aligned}$$

and the term $i = 0$ of the sum means $\text{Pf}_{z=0} \text{Tr} (a_0 F \Delta^{-z} [F, a_1] \dots [F, a_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!})$ in the right hand-side.

PROPOSITION 3.7. *The inhomogeneous (B, b) -cochains*

$$\tilde{\phi}_{2k} - \tilde{\phi}_{2k+2} - (B+b)\tilde{\gamma}_{2k+1} = \gamma_{2k} - \gamma'_{2k+2} \in CC^{2k}(\Psi_H^0(\mathbb{R}^n)) \oplus CC^{2k+2}(\Psi_H^0(\mathbb{R}^n))$$

for $0 \leq k \leq n$, viewed as cochains on $\mathcal{S}_H(\mathbb{R}^n)$, are transgression cochains between $(\psi_{2k-1}, \phi_{2k+1})$ and $(\psi_{2k+1}, \phi_{2k+3})$, that is,

$$(\psi_{2k-1} + \phi_{2k+1}) - (\psi_{2k+1} + \phi_{2k+3}) = (B+b)(\gamma_{2k} - \gamma'_{2k+2})$$

Moreover, one has

$$(3.6) \quad \begin{aligned} \gamma_{2k}(a_0, \dots, a_{2k}) \\ = \frac{k!}{2i^{k+1}(2k+1)!} \sum_{i=0}^{2k} (-1)^i \int \left(a_0 F[a_1] \dots [F, a_i] \delta F[a_{i+1}] \dots [F, a_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \end{aligned}$$

$$(3.7) \quad \begin{aligned} \gamma'_{2k}(a_0, \dots, a_{2k}) = & \int \left(a_0 \delta a_1 [F, a_2] \dots [F, a_{2k}] \otimes \frac{\omega^{n-k}}{n!} \right) \\ & + \frac{k!}{i^k(2k+1)!} \sum_{i=1}^{2k} (-1)^{i-1} \int \left(a_0 F[a_1] \dots [F, a_{i-1}] \delta a_i [F, a_{i+1}] \dots [F, a_{2k}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

That $\tilde{\phi}_{2k} - \tilde{\phi}_{2k+2} - (B+b)\tilde{\gamma}_{2k+1}$ gives a transgression cochain comes once again from the construction of a boundary map in cohomology associated to a short exact sequence. Once more, the calculations leading to these formulas are given in Appendix A.

3.4. Construction with Quillen's Algebra Cochains. The interest about Quillen's theory of cochains here is that the (B, b) -cocycles we want to get are obtained purely algebraically, since we do not need to pass first through (B, b) -cocycles on the algebra of regularizing operators. For the convenience of the reader, we briefly recall this formalism, and let him report to the original paper [10] or the Appendix B for more details.

3.4.1. *Preliminaries.* Let A an associative algebra over \mathbb{C} with unit. The *bar construction* B of A is the differential graded coalgebra $B = \bigoplus_{n \geq 0} B_n$, with $B_n = A^{\otimes n}$ for $n \geq 0$ with coproduct $\Delta : B \rightarrow B \otimes B$

$$\Delta(a_1, \dots, a_n) = \sum_{i=0}^n (a_1, \dots, a_i) \otimes (a_{i+1}, \dots, a_n)$$

The counit map η is the projection onto $A^{\otimes 0} = \mathbb{C}$, and the differential is b' :

$$b'(a_1, \dots, a_{n+1}) = \sum_{i=1}^n (-1)^{i-1} (a_1, \dots, a_i a_{i+1}, \dots, a_{n+1})$$

which is defined as the zero-map on B_0 and B_1 . These operations confer a structure of differential graded coalgebra to B .

A *bar cochain of degree n* on A is a n -linear map over A with values in an algebra L . These cochains form a complex denoted $\text{Hom}(B, L)$, whose differential is given by

$$\delta_{\text{bar}} f = (-1)^{n+1} f b'$$

for $f \in \text{Hom}^n(B, L)$. Moreover, one has a product on $\text{Hom}(B, L)$: If f and g are respectively cochains of degrees p and q , it is given by

$$fg(a_1, \dots, a_{p+q}) = (-1)^{p q} f(a_1, \dots, a_p) g(a_{p+1}, \dots, a_{p+q})$$

Therefore, $\text{Hom}(B, L)$ has a structure of differential graded algebra.

We next define Ω^B and $\Omega^{B, \natural}$ to be the following bicomodules over B :

$$\Omega^B = B \otimes A \otimes B, \quad \Omega^{B, \natural} = A \otimes B$$

Here, the \natural in exponent means that $\Omega^{B, \natural}$ is the cocommutator subspace of Ω^B . Thanks to this, one can show that the differential δ_{bar} induced on $\Omega^{B, \natural}$ is in fact the Hochschild boundary, and deduce that the complex $(\text{Hom}(\Omega^{B, \natural}, \mathbb{C}), b)$ is isomorphic to the Hochschild complex $(\text{CC}^\bullet(A), b)$ of A , with degrees shifted by one.

We recall Quillen's terminology. Let L be a differential graded algebra. Elements of $\text{Hom}(\Omega^B, L)$ will be called *Ω -cochains*, and those in $\text{Hom}(\Omega^{B, \natural}, L)$ as *Hochschild cochains*. Recall also that the *bar cochains* are the elements of $\text{Hom}(B, L)$.

REMARK 3.8. A cochain f of this kind has three degrees : a A -degree as a multilinear map over A , a L degree and a total degree f , which is sum. This is the one which will be considered.

The map $\natural : \Omega^{B, \natural} \rightarrow \Omega^B$, defined by the formula

$$\natural(a_1 \otimes (a_2, \dots, a_n)) = \sum_{i=1}^n (-1)^{i(n-1)} (a_{i+1}, \dots, a_n) \otimes a_1 \otimes (a_2, \dots, a_i)$$

induces a map from Hochschild cochains to bar cochains. If we have a (graded) trace $\tau : L \rightarrow \mathbb{C}$, we then obtain a *morphism of complexes*

$$\begin{array}{ccc} \tau^\natural : \text{Hom}(\Omega^B, L) & \longrightarrow & \text{Hom}(\Omega^{B, \natural}, \mathbb{C}) \\ f & \longmapsto & \tau^\natural(f) = \tau f \natural \end{array}$$

3.4.2. *Return to the initial problem.* We can now return to our context. Let A be the algebra $S_H^0(\mathbb{R}^n)$ of Heisenberg formal symbols on $\mathbb{R}^n = \mathbb{R}^p \times \mathbb{R}^q$, and B the bar construction of A . Also, let L be the graded algebra $S_H^0(\mathbb{R}^n) \otimes \Lambda^\bullet T^* \mathbb{R}^n$. The product on these algebras is the star-product of symbols, twisted with the product on the exterior algebra. The injection

$$\rho : A \longrightarrow L$$

is a homomorphism of algebras. As a consequence, ρ should be viewed as a 1-cochain of "curvature" zero, i.e $\delta_{\text{bar}} \rho + \rho^2 = 0$. We introduce a formal parameter ε of odd degree such that $\varepsilon^2 = 0$, and shall actually work in the extended algebra

$$\text{Hom}(B, L)[\varepsilon] = \text{Hom}(B, L) + \varepsilon \text{Hom}(B, L)$$

The role of that ε is to kill the powers of $\log|\xi|'$ which are not classical symbols, and to keep only its commutator with other symbols.

Now, denote $\nabla = F + \varepsilon \log|\xi|'$, and $\nabla^2 = F^2 + \varepsilon[\log|\xi|', F]$ the square of ∇ , and introduce the "connection" $\nabla + \delta_{\text{bar}} + \rho$. The fact that this operator does not belong to the algebra above is not a problem, since we shall only have interest in its "curvature", which is well defined,

$$K = \nabla^2 + [\nabla, \rho] = F^2 + \varepsilon[\log|\xi|', F] + [F + \varepsilon \log|\xi|', \rho]$$

and its action on $\text{Hom}(B, L)[\varepsilon]$ with commutators. Here, we emphasize that the commutators involved are in fact *graded commutators*. Let τ be the graded trace on $\text{Hom}(B, L)[\varepsilon] \otimes \Lambda^\bullet T^* \mathbb{R}^n$ given by

$$\tau(x + \varepsilon y) = \int y$$

It turns out that the cocycles (3.4) and (3.5) constructed using excision in the previous section are obtained by considering the even cochain

$$\theta = \tau(\partial\rho \cdot e^K) \in \text{Hom}(\Omega^{B, \natural}, \mathbb{C})$$

where $\partial f \cdot g$ is defined, for $f, g \in \text{Hom}(\Omega^B, L)$ of respective degrees 1 and $n-1$, by the following formula :

$$(\partial f \cdot g)\natural(a_1 \otimes (a_2, \dots, a_n)) = (-1)^{|g|} f(a_1) g(a_2, \dots, a_n)$$

The calculation of θ becomes easier if one remarks that

$$e^K = e^{F^2} \cdot e^{[F, \rho] + \varepsilon[\log|\xi|', F + \rho]}$$

as $F^2 = i\omega$ is central in L . Then, this easily provides that $\theta = \sum_k (\theta'_{2k} + \theta''_{2k})$, where

$$(3.8) \quad \theta'_{2k} = \frac{i^{n-k+1}}{(2k-1)!} \sum_{i=1}^{2k-1} \int \left(\partial\rho \cdot [F, \rho]^{i-1} \delta\rho [F, \rho]^{2k-1-i} \otimes \frac{\omega^{n-k+1}}{(n-k+1)!} \right)$$

$$(3.9) \quad \theta''_{2k} = \frac{i^{n-k}}{(2k)!} \sum_{i=0}^{2k-1} \int \left(\partial\rho \cdot [F, \rho]^i \delta F [F, \rho]^{2k-1-i} \otimes \frac{\omega^{n-k}}{(n-k)!} \right)$$

Evaluating on elements of A , this gives :

$$(3.10) \quad \begin{aligned} \theta'_{2k}(a_0, \dots, a_{2k-1}) \\ = \frac{i^{n-k+1}}{(2k-1)!} \sum_{i=1}^{2k-1} (-1)^i \int \left(a_0 [F, a_1] \dots [F, a_{i-1}] \delta a_i [F, a_{i+1}] \dots [F, a_{2k-1}] \otimes \frac{\omega^{n-k+1}}{(n-k+1)!} \right) \end{aligned}$$

$$(3.11) \quad \begin{aligned} \theta''_{2k}(a_0, \dots, a_{2k-1}) \\ = \frac{i^{n-k}}{(2k)!} \sum_{i=0}^{2k-1} (-1)^{i+1} \int \left(a_0 [F, a_1] \dots [F, a_i] \delta F [F, a_{i+1}] \dots [F, a_{2k-1}] \otimes \frac{\omega^{n-k}}{(n-k)!} \right) \end{aligned}$$

The signs above not appearing in the cochains (3.8) and (3.9) occur since the a_i , $\delta\rho$ and δF are odd.

As announced earlier, we observe that θ'_{2k} and θ''_{2k} are up to a certain constant term the cochains ϕ_{2k-1} and ψ_{2k-1} obtained in (3.4) and (3.5). The difference in signs is due to Quillen's formalism, which considers the total differential $B - b$, see Remark B.4. Unfortunately, each component of $\theta_{2k} = \theta'_{2k} + \theta''_{2k}$ of θ is not a (B, b) -cocycle, but taking the entire cochain θ into account, this is.

To prove this, it only suffices to check that all the things we defined have the good algebraic properties to fit into Quillen's proof. This is the content of the following lemma, which is actually a "Bianchi identity" with respect to the "connection" $\nabla + \delta_{\text{bar}} + \rho$.

LEMMA 3.9. (Bianchi identity.) *We have $(\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)K = (\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)e^K = 0$, where ad denotes the (graded) adjoint action.*

REMARK 3.10. The thing which guarantees this identity is that $[\nabla, \nabla] = 0$. Then, the proof is the same as that given in the paper of Quillen, [10], Section 7. Thanks to this lemma, we directly know that $(B - b)\theta = 0$, by adapting the arguments of [10], Sections 7 and 8. For the convenience of the reader, we recalled these arguments in Appendix B. This result can be refined, and we get the same results as those obtained using excision.

THEOREM 3.11. *The inhomogeneous Hochschild cochains*

$$\theta''_{2k} - \theta'_{2k+2} \in \text{Hom}^{2k}(\Omega^{B, \mathfrak{h}}, \mathbb{C}) \oplus \text{Hom}^{2k+2}(\Omega^{B, \mathfrak{h}}, \mathbb{C})$$

for $0 \leq k \leq n$, define a (B, b) -cocycle.

PROOF. Introduce a parameter $t \in \mathbb{R}$, and consider the following family of curvatures (K_t) :

$$K_t = \nabla^{2, t} + [tF + \varepsilon \log |\xi|', \rho]$$

where $\nabla^{2, t} = F^2 + \varepsilon[\log |\xi|', tF]$. Because the identity $[\nabla, \nabla^{2, t}]$ still holds, we have a Bianchi identity

$$(\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)K_t = 0$$

Thus, the Hochschild cochain

$$\theta^t = \tau^{\mathfrak{h}}(\partial\rho \cdot e^{K_t}) \in \text{Hom}(\Omega^{B, \mathfrak{h}}, \mathbb{C})[t]$$

satisfies the relation $(B - b)\theta^t = 0$ for every $t \in \mathbb{R}$, where we denote by $R[t]$ the polynomials with coefficients in an algebra R . Therefore, this relation also holds for every k , for the coefficient of t^k . This coefficient is the cochain $\theta''_{2k} + \theta'_{2k+2}$, thus, $\theta''_{2k} - \theta'_{2k+2}$ defines a (B, b) -cocycle. \square

Denote by $\Omega = [F, \rho] + \varepsilon[\log |\xi|', \rho + F]$. The cochains which cobounds these cocycles (up to modify each of them by a constant term depending on their degrees) may be obtained rather easily by using suitable linear combinations of pairs of bar cochains (μ_{2j}, μ_{2j+1}) , where μ is given by :

$$\mu_k = \tau \left(\partial\rho \cdot \frac{e^{F^2}}{k!} \sum_{i=0}^k \Omega^i F \Omega^{k-i} \right)$$

Doing this gives transgression formulas in the spirit of those obtained in Proposition 3.7.

3.5. **Index theorem.** From Proposition 3.6, we know that the Radul cocycle on $S_H^0(\mathbb{R}^n)$

$$c(a_0, a_1) = \int a_0 \delta a_1$$

where $\delta a_1 = [\log |\xi|', a_1]$, is cohomologous to the inhomogeneous (B, b) -cocycle

$$\psi_{2n-1} + \phi_{2n+1} \in \text{CC}^{2n-1}(S_H^0(\mathbb{R}^n)) \oplus \text{CC}^{2n+1}(S_H^0(\mathbb{R}^n))$$

with,

$$\psi_{2n-1}(a_0, \dots, a_{2n-1}) = \frac{1}{i^n (2n)!} \sum_{i=0}^{2n-1} (-1)^{i+1} \int a_0 [F, a_1] \dots [F, a_i] \delta F [F, a_{i+1}] \dots [F, a_{2n-1}]$$

$$\phi_{2n+1}(a_0, \dots, a_{2n+1}) =$$

$$\frac{1}{i^n (2n+1)!} \sum_{i=1}^{2n+1} (-1)^{i-1} \int a_0 [F, a_1] \dots [F, a_{i-1}] \delta a_i [F, a_{i+1}] \dots [F, a_{2n+1}]$$

We shall now compute $\psi_{2n-1} + \phi_{2n+1}$ to obtain an index theorem. To begin, we first notice that by Lemma 3.3, we may rewrite the cocycles above as

$$(3.12) \quad \psi_{2n-1}(a_0, \dots, a_{2n-1}) = \frac{i^{2n-1}}{i^n(2n)!} \sum_{i=0}^{2n-1} (-1)^{i+1} \int a_0 da_1 \dots da_i \delta F da_{i+1} \dots da_{2n-1}$$

$$(3.13) \quad \phi_{2n+1}(a_0, \dots, a_{2n+1}) = \frac{i^{2n-1}}{i^n(2n+1)!} \sum_{i=1}^{2n+1} (-1)^{i-1} \int a_0 da_1 \dots da_{i-1} \delta a_i da_{i+1} \dots da_{2n+1}$$

The construction of the Wodzicki residue to $\Lambda^\bullet T^* \mathbb{R}^n$ -valued symbols in the Paragraph 3.2 imposes that the \int selects only the coefficient associated to the volume form $dx_1 \dots dx_n d\xi_1 \dots d\xi_n$. In (3.13), this coefficient must be a sum of terms of the form $\frac{\partial b_1}{\partial x_1} \dots \frac{\partial b_n}{\partial x_n} \frac{\partial b_{n+1}}{\partial \xi_1} \dots \frac{\partial b_{2n}}{\partial \xi_n}$ for some Heisenberg symbols b_1, \dots, b_{2n} of order 0. Such terms have Heisenberg pseudodifferential order $-(p+2q)$.

However, in (3.13), there is in each sum an additional factor of the form δa_i , which is a symbol of degree -1 . Hence, the symbols appearing in the formula are at most of Heisenberg order $-(p+2q+1)$, and vanishes because of (3.1).

The formula for the cocycle (3.12) also reduces to a more simple one, but which is in general non-zero. A simple computation gives that

$$\delta F = i \left(\sum_{i=1}^p \frac{\xi_i^3 d\xi_i}{|\xi|'^4} + \frac{1}{2} \sum_{i=p+1}^n \frac{\xi_i d\xi_i}{|\xi|'^4} \right)$$

Then, we proceed as we did to obtain the formula (3.13). The coefficient on $dx_1 \dots dx_n d\xi_1 \dots d\xi_n$ of the symbols in (3.12) must be of the form

- (i) $\frac{\partial b_1}{\partial x_1} \dots \frac{\partial b_n}{\partial x_n} \frac{\partial b_{n+1}}{\partial \xi_1} \dots \frac{\xi_i^3}{|\xi|'^4} \dots \frac{\partial b_{2n}}{\partial \xi_n}$ if $1 \leq i \leq p$,
- (ii) $\frac{\partial b_1}{\partial x_1} \dots \frac{\partial b_n}{\partial x_n} \frac{\partial b_{n+1}}{\partial \xi_1} \dots \frac{\xi_i}{|\xi|'^4} \dots \frac{\partial b_{2n}}{\partial \xi_n}$ if $p+1 \leq i \leq n$

where in each point, the term depending on $|\xi|'^4$ replaces the term $\frac{\partial b_{n+i}}{\partial \xi_i}$. In all case, these terms are of order $-(p+2q)$. Thus, if we denote the Heisenberg principal symbol by

$$\sigma : \mathcal{S}_H^0(\mathbb{R}^n) \longrightarrow C^\infty(S_H^* \mathbb{R}^n)$$

the symbol of order $-(p+2q)$ of $a_0 da_1 \dots da_i \delta F da_{i+1} \dots da_{2n-1}$ is

$$\sigma(a_0) d\sigma(a_1) \dots d\sigma(a_i) \delta F d\sigma(a_{i+1}) \dots d\sigma(a_{2n-1}) = (-1)^i \delta F \sigma(a_0) d\sigma(a_1) \dots d\sigma(a_{2n-1})$$

We emphasize that the latter product is no more the star-product but the usual product of functions.

The vector field $L = \sum_{j=1}^p \xi_j \partial_{\xi_j} + 2 \sum_{j=p+1}^n \xi_j \partial_{\xi_j}$ on $T^* \mathbb{R}^n$ is the generator of the Heisenberg dilations. This implies that $\iota_L d\sigma(a_i) = d\sigma(a_i) \cdot L = 0$ since the a_i are symbols of order 0. Using (3.1), and observing that $\iota_L \delta F = i$, we obtain

$$\psi_{2n-1}(a_0, \dots, a_{2n-1}) = -\frac{1}{(2\pi i)^n (2n-1)!} \int_{S_H^* \mathbb{R}^n} \sigma(a_0) d\sigma(a_1) \dots d\sigma(a_{2n-1})$$

So, we have proved the following theorem

THEOREM 3.12. *The Radul cocycle is (B, b) -cohomologous to the homogeneous (B, b) -cocycle on $\mathcal{S}_H(\mathbb{R}^n)$ defined by*

$$\psi_{2n-1}(a_0, \dots, a_{2n-1}) = -\frac{1}{(2\pi i)^n (2n-1)!} \int_{S_H^* \mathbb{R}^n} \sigma(a_0) d\sigma(a_1) \dots d\sigma(a_{2n-1})$$

From this theorem, Formula (2.2), and the odd pairing of cyclic cohomology with K-theory, given for any $[\phi] \in \text{HP}^1(\mathcal{S}_H(\mathbb{R}^n))$ and $[\mathbf{u}] \in \text{K}_1(\mathcal{S}_H(\mathbb{R}^n))$ by the formula

$$\langle [\phi], [\mathbf{u}] \rangle = \sum_{k \geq 0} (-1)^k k! (\phi_{2k+1} \otimes \text{tr})(\mathbf{u}^{-1}, \mathbf{u}, \dots, \mathbf{u}^{-1}, \mathbf{u})$$

one has the following topological index formula for Heisenberg elliptic pseudodifferential operators of order 0, which only depends on their principal symbol. Here, tr denotes the trace of matrices.

THEOREM 3.13. *Let $P \in M_N(\Psi_H^0(\mathbb{R}^n))$ be a Heisenberg elliptic pseudodifferential operator of symbol $\mathbf{u} \in \text{GL}_N(\mathcal{S}_H^0(\mathbb{R}^n))$, and $[\mathbf{u}] \in \text{K}_1(\mathcal{S}_H^0(\mathbb{R}^n))$ its (odd) K-theory class. Then, we have a formula for the Fredholm index of P :*

$$\text{Ind}(P) = \text{Tr}(\text{Ind}[\mathbf{u}]) = \frac{(-1)^n (n-1)!}{(2\pi i)^n (2n-1)!} \int_{S_H^* \mathbb{R}^n} \text{tr}(\sigma(\mathbf{u})^{-1} d\sigma(\mathbf{u})(d\sigma(\mathbf{u})^{-1} d\sigma(\mathbf{u}))^{n-1})$$

APPENDIX A. COMPUTATIONS OF SECTION 3.1

We give here the details of the different computations allowing to derive the different formulas of Section 3.

A.1. Cocycles formulas. Recall that

$$\begin{aligned} & \tilde{\Phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k}) \\ &= \frac{k!}{i^k (2k)!} \frac{1}{2k+1} \sum_{i=0}^{2k} \text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0 [\mathbf{F}, \mathbf{a}_1] \dots [\mathbf{F}, \mathbf{a}_i] \Delta^{-z/4} [\mathbf{F}, \mathbf{a}_{i+1}] \dots [\mathbf{F}, \mathbf{a}_{2k}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

FORMULA (3.4). We compute $\psi_{2k-1} = \text{B}\tilde{\Phi}_{2k}$

$$\begin{aligned} & \text{B}\tilde{\Phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \\ &= \frac{k!}{i^k (2k)!} \frac{1}{2k+1} \sum_{i=0}^{2k} \text{Pf}_{z=0} \text{Tr} \left[\left([\mathbf{F}, \mathbf{a}_0] \dots [\mathbf{F}, \mathbf{a}_i] \Delta^{-z/4} [\mathbf{F}, \mathbf{a}_{i+1}] \dots [\mathbf{F}, \mathbf{a}_{2k-1}] \right. \right. \\ & \quad \left. \left. - [\mathbf{F}, \mathbf{a}_{2k-1}] [\mathbf{F}, \mathbf{a}_0] \dots [\mathbf{F}, \mathbf{a}_{i-1}] \Delta^{-z/4} [\mathbf{F}, \mathbf{a}_i] \dots [\mathbf{F}, \mathbf{a}_{2k-2}] + \dots \right. \right. \\ & \quad \left. \left. + (-1)^{2k-1} [\mathbf{F}, \mathbf{a}_1] \dots [\mathbf{F}, \mathbf{a}_{i+1}] \Delta^{-z/4} [\mathbf{F}, \mathbf{a}_{i+2}] \dots [\mathbf{F}, \mathbf{a}_{2k-1}] [\mathbf{F}, \mathbf{a}_0] \right) \otimes \frac{\omega^{n-k}}{n!} \right] \end{aligned}$$

Then, by the graded trace property, one can remark that all the terms of the sum $\sum_{i=0}^{2k} \dots$ are similar, so, this sum equals $(2k+1)$ times the term $i=0$.

$$\begin{aligned} & \text{B}\tilde{\Phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \\ &= \frac{k!}{i^k (2k)!} \text{Pf}_{z=0} \text{Tr} \left[\left([\mathbf{F}, \mathbf{a}_0] \dots [\mathbf{F}, \mathbf{a}_{2k-1}] \Delta^{-z/4} - [\mathbf{F}, \mathbf{a}_{2k-1}] [\mathbf{F}, \mathbf{a}_0] \dots [\mathbf{F}, \mathbf{a}_{2k-2}] \Delta^{-z/4} \right. \right. \\ & \quad \left. \left. + \dots + (-1)^{2k-1} [\mathbf{F}, \mathbf{a}_1] \dots [\mathbf{F}, \mathbf{a}_{2k-1}] [\mathbf{F}, \mathbf{a}_0] \Delta^{-z/4} \right) \otimes \frac{\omega^{n-k}}{n!} \right] \\ &= \frac{k!}{i^k (2k)!} \sum_{i=0}^{2k-1} \text{Pf}_{z=0} \text{Tr} \left([\mathbf{F}, \mathbf{a}_0] \dots [\mathbf{F}, \mathbf{a}_i] \Delta^{-z/4} [\mathbf{F}, \mathbf{a}_{i+1}] \dots [\mathbf{F}, \mathbf{a}_{2k-1}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

where we used the graded trace property in the second equality. Then, writing $[F, \mathbf{a}_0] = F\mathbf{a}_0 - \mathbf{a}_0F$, using the fact that F anticommutes with the $[F, \mathbf{a}_i]$ and the graded trace property again, we obtain

$$\begin{aligned} & \widetilde{\mathbf{b}}\Phi_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \\ &= \frac{k!}{\mathbf{i}^k(2k)!} \sum_{i=0}^{2k-1} \text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0[F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] ((-1)^{2k-i} \Delta^{-z/4} F - (-1)^i F \Delta^{-z/4}) [F, \mathbf{a}_{i+1}] \right. \\ & \qquad \qquad \qquad \left. \dots [F, \mathbf{a}_{2k-1}] \otimes \frac{\omega^{n-k}}{n!} \right) \\ &= \frac{k!}{\mathbf{i}^k(2k)!} \sum_{i=0}^{2k-1} (-1)^{i+1} \text{Res}_{z=0} \text{Tr} \left(\mathbf{a}_0[F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] \frac{[F, \Delta^{-z/4}]}{z} [F, \mathbf{a}_{i+1}] \right. \\ & \qquad \qquad \qquad \left. \dots [F, \mathbf{a}_{2k-1}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

From Theorem 2.1, or, to be more precise, the part of the proof allowing to pass from the Partie Finie to the residue, we finally obtain

$$\begin{aligned} & \widetilde{\mathbf{b}}\Phi_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \\ &= \frac{k!}{\mathbf{i}^k(2k)!} \sum_{i=0}^{2k-1} (-1)^{i+1} \int \left(\mathbf{a}_0[F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] \delta F [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k-1}] \otimes \frac{\omega^{n-k}}{n!} \right) \\ &= \Psi_{2k-1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k-1}) \end{aligned}$$

□

FORMULA (3.5). We now compute $\phi_{2k+1} = \mathbf{b}\widetilde{\Phi}_{2k}$. As $[F, \cdot]$ is an derivation on $\mathcal{S}_H(\mathbb{R}^n)$, the following equality may be observed easily

$$\begin{aligned} \mathbf{b}\widetilde{\Phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) &= \frac{k!}{\mathbf{i}^k(2k+1)!} \sum_{i=0}^{2k} (-1)^i \text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0[F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] [\mathbf{a}_{i+1}, \Delta^{-z/4}] \right. \\ & \qquad \qquad \qquad \left. [F, \mathbf{a}_{i+2}] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k}}{n!} \right) \end{aligned}$$

Again, from the proof of Theorem 2.1, we finally have

$$\begin{aligned} & \mathbf{b}\widetilde{\Phi}_{2k}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) \\ &= \frac{k!}{\mathbf{i}^k(2k+1)!} \sum_{i=1}^{2k+1} (-1)^{i-1} \int \left(\mathbf{a}_0[F, \mathbf{a}_1] \dots [F, \mathbf{a}_{i-1}] \delta \mathbf{a}_i [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k}}{n!} \right) \\ &= \Phi_{2k+1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) \end{aligned}$$

□

A.2. Transgression formulas. We now give the details of the computations needed to obtain the formulas of Proposition 3.7. Recall that

$$\begin{aligned} & \widetilde{\Upsilon}_{2k+1}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+1}) \\ &= \frac{(k+1)!}{\mathbf{i}^{k+1}(2k+2)!} \frac{1}{2k+3} \left[\text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0 \Delta^{-z/4} F [F, \mathbf{a}_1] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right. \\ & \qquad \qquad \qquad \left. + \sum_{i=0}^{2k+1} \text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0 F [F, \mathbf{a}_1] \dots [F, \mathbf{a}_i] \Delta^{-z} [F, \mathbf{a}_{i+1}] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right] \end{aligned}$$

where the term $i = 0$ of the sum means $\text{Pf}_{z=0} \text{Tr} \left(\mathbf{a}_0 F \Delta^{-z} [F, \mathbf{a}_1] \dots [F, \mathbf{a}_{2k+1}] \otimes \frac{\omega^{n-k-1}}{n!} \right)$.

FORMULA (3.6). We compute $B\tilde{\gamma}_{2k+1}(a_0, \dots, a_{2k})$. By the graded trace property, applying the operator B to each term of $\tilde{\gamma}_{2k+1}$ yields the same contribution. As there are $(2k+3)$ terms, we have

$$B\tilde{\gamma}_{2k+1}(a_0, \dots, a_{2k}) = \frac{(k+1)!}{i^{k+1}(2k+2)!} \text{Pf}_{z=0} \text{Tr} \left([F, a_0] \dots [F, a_{2k}] \right. \\ \left. + F[F, a_{2k}][F, a_0] \dots [F, a_{2k-1}] + \dots + F[F, a_1] \dots F[F, a_{2k}][F, a_0] \right) \Delta^{-z/4} \otimes \frac{\omega^{n-k-1}}{n!}$$

Writing $\frac{(k+1)!}{(2k+2)!} = \frac{1}{2} \frac{k!}{(2k+1)!}$, knowing that F anticommutes to the $[F, a_i]$ and that $F^2 = i\omega$ is central, developing $F[F, a_0]$ and finally using the graded trace property, we obtain

$$B\tilde{\gamma}_{2k+1}(a_0, \dots, a_{2k}) \\ = \frac{k!}{i^{k+1}(2k+1)!} \cdot \frac{1}{2} \sum_{i=0}^{2k} \text{Pf}_{z=0} \left((a_0 F^2 - F a_0 F) [F, a_1] \dots \Delta^{-z/4} \dots [F, a_{2k}] \otimes \frac{\omega^{n-k-1}}{n!} \right)$$

Once again using that $F^2 = i\omega$, we can write

$$\tilde{\phi}_{2k}(a_0, \dots, a_{2k}) \\ = \frac{k!}{i^{k+1}(2k+1)!} \sum_{i=0}^{2k} \text{Pf}_{z=0} \text{Tr} \left(a_0 F^2 [F, a_1] \dots [F, a_i] \Delta^{-z/4} [F, a_{i+1}] \dots [F, a_{2k}] \otimes \frac{\omega^{n-k-1}}{n!} \right)$$

hence,

$$(\tilde{\phi}_{2k} - B\tilde{\gamma}_{2k+1})(a_0, \dots, a_{2k}) \\ = \frac{k!}{i^{k+1}(2k+1)!} \cdot \frac{1}{2} \sum_{i=0}^{2k} \text{Pf}_{z=0} \left((a_0 F^2 + F a_0 F) [F, a_1] \dots \Delta^{-z/4} \dots [F, a_{2k}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \\ = \frac{k!}{i^{k+1}(2k+1)!} \cdot \frac{1}{2} \sum_{i=0}^{2k} \text{Pf}_{z=0} \left(a_0 F [F, a_1] \dots ((-1)^i F \Delta^{-z/4} - (-1)^{2k-i} \Delta^{-z/4} F) \right. \\ \left. \dots [F, a_{2k}] \otimes \frac{\omega^{n-k-1}}{n!} \right)$$

Finally, we obtain

$$(\tilde{\phi}_{2k} - B\tilde{\gamma}_{2k+1})(a_0, \dots, a_{2k}) \\ = \frac{k!}{2i^{k+1}(2k+1)!} \sum_{i=0}^{2k} (-1)^i \int \left(a_0 F [F, a_1] \dots \delta F \dots [F, a_{2k}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \\ = \gamma_{2k}(a_0, \dots, a_{2k})$$

□

FORMULA (3.7). We now calculate $b\tilde{\gamma}_{2k+1}$. Writing $a_1 F = -[F, a_1] + F a_1$ and using the derivation property of $[F, \cdot]$,

$$b\tilde{\gamma}_{2k+1}(a_0, \dots, a_{2k+2}) \\ = -\tilde{\phi}_{2k+2}(a_0, \dots, a_{2k+2}) \\ + \frac{(k+1)!}{i^{k+1}(2k+3)!} \left[\text{Pf}_{z=0} \left(a_0 [a_1, \Delta^{-z/4}] [F, a_2] \dots [F, a_{2k+2}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right. \\ \left. + \sum_{i=0}^{2k+1} (-1)^i \text{Pf}_{z=0} \left(a_0 F [F, a_1] \dots [a_{i+1}, \Delta^{-z/4}] [F, a_2] \dots [F, a_{2k+2}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right]$$

Finally,

$$\begin{aligned}
& (\tilde{\Phi}_{2k+2} + b\tilde{\gamma}_{2k+1})(\mathbf{a}_0, \dots, \mathbf{a}_{2k+2}) \\
&= \frac{(k+1)!}{i^{k+1}(2k+3)!} \left[\int \left(\mathbf{a}_0 \delta \mathbf{a}_1 [F, \mathbf{a}_2] \dots [F, \mathbf{a}_{2k+2}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right. \\
&\quad \left. + \sum_{i=1}^{2k+2} (-1)^{i-1} \int \left(\mathbf{a}_0 F [F, \mathbf{a}_1] \dots \delta \mathbf{a}_i \dots [F, \mathbf{a}_{2k+2}] \otimes \frac{\omega^{n-k-1}}{n!} \right) \right] \\
&= \gamma_{2k+2}(\mathbf{a}_0, \dots, \mathbf{a}_{2k+2})
\end{aligned}$$

□

APPENDIX B. COMPLEMENTS ON SECTION 3.2

For the convenience of the reader, we recall here Quillen's picture of (B, b) -cocycles and how it is used to obtain Theorem 3.11 from the Bianchi identity of Lemma 3.9.

B.1. More on Quillen's formalism. Let A be an associative algebra over \mathbb{C} , and B be the bar construction of A . Recall that Ω^B and $\Omega^{B, \natural}$ are the following bicomodules over B :

$$\Omega^B = B \otimes A \otimes B, \quad \Omega^{B, \natural} = A \otimes B$$

THEOREM B.1. *One has a complex of period 2*

$$\dots \xrightarrow{\bar{\partial}} B \xrightarrow{\beta} \Omega^{B, \natural} \xrightarrow{\bar{\partial}} B \xrightarrow{\beta} \dots$$

with $\bar{\partial} = \partial_{\natural} : \Omega^{B, \natural} \rightarrow B$, where $\natural : \Omega^{B, \natural} \rightarrow \Omega^B$, $\partial : \Omega^B \rightarrow B$, $\beta : B \rightarrow \Omega^{B, \natural}$ are defined by the following formulas :

$$\begin{aligned}
\natural(\mathbf{a}_1 \otimes (\mathbf{a}_2, \dots, \mathbf{a}_n)) &= \sum_{i=1}^n (-1)^{i(n-1)} (\mathbf{a}_{i+1}, \dots, \mathbf{a}_n) \otimes \mathbf{a}_1 \otimes (\mathbf{a}_2, \dots, \mathbf{a}_i) \\
\partial(\mathbf{a}_1, \dots, \mathbf{a}_{p-1}) \otimes \mathbf{a}_p \otimes (\mathbf{a}_{p+1}, \dots, \mathbf{a}_n) &= (\mathbf{a}_1, \dots, \mathbf{a}_n) \\
\bar{\partial}(\mathbf{a}_1 \otimes (\mathbf{a}_2, \dots, \mathbf{a}_n)) &= \sum_{i=1}^n (-1)^{i(n-1)} (\mathbf{a}_{i+1}, \dots, \mathbf{a}_n, \mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_i) \\
\beta(\mathbf{a}_1, \dots, \mathbf{a}_n) &= (-1)^{n-1} \mathbf{a}_n \otimes (\mathbf{a}_1, \dots, \mathbf{a}_{n-1}) - \mathbf{a}_1 \otimes (\mathbf{a}_2, \dots, \mathbf{a}_n)
\end{aligned}$$

As Quillen shows in [10], it turns out that the 2-periodic complex constructed above is exactly the Loday-Quillen cyclic bicomplex with degrees shifted by one, and is therefore equivalent to Connes (B, b) -bicomplex. The shift of the degrees makes that elements of the algebra A become odd in the bar construction, while they are even in the cyclic bicomplex.

Now, let L be a differential graded algebra. The maps $\bar{\partial}$ and β of the periodic complex induces maps from bar cochains to Hochschild cochains (with values in L) and conversely by pull-back. The following formula is a key step.

LEMMA B.2. *Let $f, g \in \text{Hom}(B, L)$ be bar cochains. Then, we have*

$$\beta(\tau^{\natural}(\partial f \cdot g)) = -\tau([f, g])$$

We carry a purely computational proof, because of the way we introduced Quillen's formalism. A more elegant and conceptual proof is given in Quillen's article [10], paragraph 5.2. The proof of this lemma is based on the following formula,

$$(B.1) \quad (\partial f \cdot g)\natural(\mathbf{a}_1 \otimes (\mathbf{a}_2, \dots, \mathbf{a}_n)) = \sum_{n-p < i \leq n} (-1)^{i(n-1)} (f \cdot g)(\mathbf{a}_{i+1}, \dots, \mathbf{a}_n, \mathbf{a}_1, \dots, \mathbf{a}_i)$$

where f and g be bar cochains of respective degrees p and $n - p$. The case $p = 1$ will be often used, so we give it :

$$(B.2) \quad (\partial f \cdot g)\natural(a_1 \otimes (a_2, \dots, a_n)) = (-1)^{|g|} f(a_1) g(a_2, \dots, a_n)$$

PROOF. Let f and g be bar cochains of respective degrees p and $n - p$. By definition, $\beta(\tau^\natural(\partial f \cdot g)) = \tau(\partial f \cdot g)\natural\beta$, and using (B.1), so,

$$\begin{aligned} & \beta(\tau^\natural(\partial f \cdot g))(a_1, \dots, a_n) \\ &= \tau(\partial f \cdot g)\natural(((-1)^{n-1} a_n \otimes (a_1, \dots, a_{n-1}) - a_1 \otimes (a_2, \dots, a_n)) \\ &= \tau \left(\sum_{n-p < i \leq n} (-1)^{n-1} (-1)^{i(n-1)} (f \cdot g)(a_i, \dots, a_n, a_1, \dots, a_{i-1}) \right. \\ & \qquad \qquad \qquad \left. - \sum_{n-p < i \leq n} (-1)^{i(n-1)} (f \cdot g)(a_{i+1}, \dots, a_n, a_1, \dots, a_i) \right) \end{aligned}$$

The first sum of the last equality can be rewritten

$$\begin{aligned} & \sum_{n-p < i \leq n} (-1)^{n-1} (-1)^{i(n-1)} (f \cdot g)(a_i, \dots, a_n, a_1, \dots, a_{i-1}) \\ &= \sum_{n-p-1 < i \leq n-1} (-1)^{i(n-1)} (f \cdot g)(a_{i+1}, \dots, a_n, a_1, \dots, a_i) \end{aligned}$$

and noting that $(-1)^{n(n-1)} = 1$, we obtain

$$\begin{aligned} & \beta(\tau^\natural(\partial f \cdot g))(a_1, \dots, a_n) \\ &= \tau((-1)^{(n-p)(n-1)} (f \cdot g)(a_{n-p+1}, \dots, a_n, a_1, \dots, a_{n-p}) - (f \cdot g)(a_1, \dots, a_n)) \\ &= \tau((-1)^{(n-p)(n-1)} (-1)^{p|g|} f(a_{n-p+1}, \dots, a_n) g(a_1, \dots, a_{n-p}) - (f \cdot g)(a_1, \dots, a_n)) \\ &= \tau((-1)^{(n-p)(n-1)} (-1)^{p|g|} (-1)^{(|f|+p)(|g|+n-p)} g(a_1, \dots, a_{n-p}) f(a_{n-p+1}, \dots, a_n) \\ & \qquad \qquad \qquad - (f \cdot g)(a_1, \dots, a_n)) \\ &= \tau((-1)^{(n-p)(n-p-1)} (-1)^{|f| \cdot |g|} (g \cdot f)(a_1, \dots, a_{n-p}, a_{n-p+1}, \dots, a_n) \\ & \qquad \qquad \qquad - (f \cdot g)(a_1, \dots, a_n)) \end{aligned}$$

where we used the (graded) trace property of τ in the third equality.

As we have $(-1)^{(n-p)(n-p-1)} = 1$, this yields the result. \square

We can now give Quillen's picture of (B, b) -cocycles.

THEOREM B.3. *Let $\theta \in \text{Hom}(\Omega^{B, \natural}, \mathbb{C})$ be a Hochschild cochain, and $\eta \in \text{Hom}(B, \mathbb{C})$ be the bar cochain defined by*

$$\eta_k(a_1, \dots, a_k) = \theta(1, a_1, \dots, a_k)$$

Suppose that for each k , we have

$$\delta_{\text{bar}} \eta_k = (-1)^k \beta \theta_{k+1}, \quad \delta_{\text{bar}} \theta_{k+1} = (-1)^k \bar{\partial} \eta_{k+2}$$

and that in addition, $\theta_{n+1}(a_0, a_1, \dots, a_n) = 0$ if $a_i = 1$, for $i \geq 1$.

Then, for all k , $B\theta_{k+1} = b\theta_{k-1}$.

REMARK B.4. This means that if we redefine signs correctly in θ , we obtain a (B, b) -cocycle in our sign conventions.

B.2. Complements on Remark 3.10. We give here the details of Quillen's arguments. The only thing we have done towards the original paper [10] is to mix the arguments of Sections 7 and 8.

LEMMA B.5. (Bianchi identity.) *We have $(\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)K = (\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)e^K = 0$, where ad denotes the (graded) adjoint action.*

PROOF. Let D be the derivation $\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla$. It suffices to check that $D(K) = 0$, the other equality will follow in virtue of the differentiation formula

$$D(e^K) = \int_0^1 e^{(1-s)K} D(K) e^{sK} ds$$

We first remark that $[\nabla, \nabla^2] = 0$, using that ε commutes (in the graded sense) with elements of $\text{Hom}(B, L)$ and that $\varepsilon^2 = 0$. Furthermore $\delta_{\text{bar}}\nabla^2 = 0$ since δ_{bar} vanishes on 0-cochains. Therefore,

$$\begin{aligned} D(K) &= (\delta_{\text{bar}} + \text{ad}\rho + \text{ad}\nabla)(\nabla^2 + [\nabla, \rho]) \\ &= \delta_{\text{bar}}[\nabla, \rho] + [\rho, [\nabla, \rho]] + [\rho, \nabla^2] + [\nabla, [\nabla, \rho]] \\ &= [\nabla, \rho^2] + \rho[\nabla, \rho] - [\nabla, \rho]\rho + [\rho, \nabla^2] + [\nabla^2, \rho] \\ &= 0 \end{aligned}$$

The result is proved. □

According to Theorem B.3, let us define the bar cochain $\eta \in \text{Hom}(B, \mathbb{C})$:

$$\eta_{2k-1}(a_1, \dots, a_{2k-1}) = \theta_{2k}(1, a_1, \dots, a_{2k+1})$$

Also remark that $\eta = \tau(e^K)$.

PROPOSITION B.6. *The bar and Hochschild cochains η and θ satisfies the relations*

$$\delta_{\text{bar}}\eta = \pm\beta\theta, \quad \delta_{\text{bar}}\theta = \pm\bar{\partial}\eta$$

The \pm means that the sign is positive in the even case and negative in the odd case.

PROOF. For the first formula of the proposition, we have

$$\delta_{\text{bar}}\eta = \delta_{\text{bar}}(\tau(e^K)) = \tau(\delta_{\text{bar}}e^K) = \tau(\delta_{\text{bar}}e^K + [\nabla, e^K]) = -\tau([\rho, e^K]) = \pm\beta(\tau^{\natural}(\partial\rho \cdot e^K))$$

The second equality uses the trace property of τ , the third is the Bianchi identity of the lemma above, and the last one is Lemma B.2.

For the second formula, first recall that $\delta_{\text{bar}}\rho + \rho^2 = 0$. Then, one has :

$$\begin{aligned} \delta_{\text{bar}}(\tau^{\natural}(\partial\rho \cdot e^K)) &= \tau^{\natural}(\partial(-\rho^2)e^K - \partial\rho \cdot \delta_{\text{bar}}e^K) \\ 0 &= \tau^{\natural}([\rho, \partial\rho \cdot e^K]) = \tau^{\natural}((\rho \cdot \partial\rho + \partial\rho \cdot \rho)e^K - \partial\rho \cdot [\rho, e^K]) \\ 0 &= \tau^{\natural}([\nabla, \partial\rho \cdot e^K]) = \tau^{\natural}(\partial[\nabla, \rho]e^K - \partial\rho \cdot [\nabla, e^K]) \end{aligned}$$

Adding these three equations, using Bianchi identity and $\delta_{\text{bar}}\rho + \rho^2 = 0$ yields

$$\delta_{\text{bar}}(\tau^{\natural}(\partial\rho \cdot e^K)) = \tau^{\natural}(\partial[\nabla, \rho]e^K) = \tau^{\natural}(\partial K \cdot e^K)$$

The last equality follows from the definition of K . Moreover,

$$\bar{\partial}(e^K) = \tau^{\natural}(\partial e^K) = \int_0^1 \tau^{\natural}(e^{(1-t)K} \cdot \partial K \cdot e^{tK}) dt = \tau^{\natural}(\partial K \cdot e^K)$$

where last equality stands because of the trace property. This concludes the proof. □

Hence, Theorem B.3 shows that θ gives rise to a (B, b) -cocycle (up to changing signs). The same arguments may be used to complete the proof of Theorem 3.11.

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