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Analytic regularity for solutions to sums of squares: an assessment

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# ANALYTIC REGULARITY FOR SOLUTIONS TO SUMS OF SQUARES: AN ASSESSMENT

ANTONIO BOVE AND MARCO MUGHETTI

*In memory of Nick Hanges*

ABSTRACT. We present a brief survey on the state of the theory of the real analytic regularity (real analytic hypoellipticity) for the solutions to sums of squares of vector fields satisfying the Hörmander condition.

## CONTENTS

1. Introduction: the $C^\infty$ hypoellipticity	1
2. The real analytic case: a short history, examples and counterexamples	5
3. Geometry of the characteristic variety: stratifications and the Treves conjecture	10
3.1. The analytic stratification	11
3.2. The symplectic stratification	12
3.3. The Poisson stratification	13
4. Examples and counterexamples	15
4.1. Examples	16
4.2. Counterexamples	18
5. Open problems	28
5.1. The 2 dimensional case	28
5.2. The 3 dimensional case	30
5.3. The case of dimension $n \geq 3$	33
References	34

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1. INTRODUCTION: THE  $C^\infty$  HYPOELLIPTICITY

The purpose of the present paper is to give an account of the actual status of the theory of the real analytic regularity for the solutions to sums of squares type equations.

While the problem of the  $C^\infty$  hypoellipticity of sums of squares has been settled from the very beginning by the famous paper of L. Hörmander, [34], the problem of the analytic hypoellipticity is still open and seems much more involved than the latter.

In this section we give a brief presentation of the results in the  $C^\infty$  category, since they have been the starting point of any further study. We tried to give all the references we are aware of, but by no means we claim completeness.

Consider an equation of the form

$$\sum_{i,j=1}^n a_{i,j}(x) \partial_i \partial_j u(x) + \sum_{j=1}^n b_j(x) u(x) + c(x) u(x) = f(x).$$

We say that it is a degenerate elliptic equation if the quadratic form corresponding to the principal symbol is non negative (or non positive, depending on the sign conventions):

$$\sum_{i,j=1}^n a_{i,j}(x) \xi_i \xi_j \geq 0.$$

Let us start by assuming that the coefficients of the above equation are smooth, i.e.  $C^\infty$  functions defined in an open subset  $\Omega \subset \mathbb{R}^n$ . Even then the problem of the regularity of the distribution solutions when the data are smooth seems too general. But if we assume that the matrix

$$A(x) = [a_{i,j}(x)]_{\substack{i=1,\dots,n \\ j=1,\dots,n}}$$

has constant rank near a point where its determinant vanishes, then, at least locally, we may find a finite number of vector fields

$$(1.1) \quad X_j(x, D_x) = \sum_{k=1}^n \alpha_{j,k}(x) D_k, \quad j = 0, 1, \dots, r,$$

such that the above operator is written as

$$\sum_{j=1}^r X_j(x, D)^2 + X_0(x, D) + \alpha(x),$$

(see also the fundamental paper [34].)

In what follows we focus on operators of the form

$$(1.2) \quad P(x, D) = \sum_{j=1}^r X_j(x, D)^2,$$

where  $X_j$  denotes a vector field with smooth (or real analytic) coefficients,  $a_{j,k}(x)$ , with  $a_{j,k} \in C^\infty(\Omega)$  or  $a_{j,k} \in C^\omega(\Omega)$ , the latter denoting the class of all real analytic functions on  $\Omega$ .

In the paper [34] Hörmander proved for a slightly more general class of operators than the one in (1.2) the following

**Proposition 1.1** ([34]). *If  $P$  is a second order differential operator and  $P$  is  $C^\infty$  hypoelliptic in the open subset  $\Omega$ , then the principal symbol of  $P$  is semidefinite.*

Here is the famous result on the  $C^\infty$  hypoellipticity for operators of the form (1.2)

**Theorem 1.1** ([34]). *Let  $P$  be given by (1.2), where the vector fields have  $C^\infty$  coefficients in the open set  $\Omega \subset \mathbb{R}^n$ . Assume that among the operators  $X_{j_1}, [X_{j_1}, X_{j_2}], \dots, [X_{j_1}, [X_{j_2}, [X_{j_3}, \dots, X_{j_k}]]], \dots$ , where  $j_\ell = 1, 2, \dots, r$ , there exist  $n$  which are linearly independent at any given point in  $\Omega$ . Then  $P$  is  $C^\infty$  hypoelliptic.*

The condition on the vector fields appearing in Theorem 1.1 has been stated literally as Hörmander stated it, but it has a deep geometric meaning. In fact by  $[X, Y]$  we denote the commutator of the vector fields:  $[X, Y]u = XYu - YXu$ . We easily see that  $[X, Y]$  is a vector field and that

$$[X, Y] = \sum_{j,k=1}^n (a_j(x)\partial_j b_k(x) - b_j(x)\partial_j a_k(x)) \partial_k,$$

where  $a_j, b_k$  denote the (smooth) coefficients of  $X$  and  $Y$ , respectively.

The condition in Theorem 1.1 can then be rephrased as

**Hörmander's Condition:**

The Lie algebra over the open set  $\Omega$  generated by the vector fields  $X_j$  and their brackets has dimension  $n$ , i.e. the dimension of the ambient space.

Derridj, in [22], proved that if the coefficients of the vector fields have real analytic regularity, then the Hörmander Condition (HC for short) is also necessary.

Theorem 1.1 has received a lot of attention over the years and we would like to mention the extensions that are particularly meaningful in the discussion of the real analytic hypoellipticity.

We first remark that the proof of the hypoellipticity of the operator  $P$  is done by establishing an a priori inequality showing the loss of derivatives of the operator  $P$ . The inequality with the optimal loss of derivatives is due to Rothschild and Stein, [51].

**Theorem 1.2.** *Let  $x_0 \in \Omega$  and denote by  $U$  a neighborhood of  $x_0$ ,  $U \subset \Omega$ . Assume that in  $U$  the Hörmander Condition is satisfied by taking iterated brackets involving at most  $m$  vector fields. Then for every  $u \in C_0^\infty(U)$  there is a positive constant  $C$  such that*

$$(1.3) \quad \|u\|_{\frac{1}{m}}^2 + \sum_{j=1}^r \|X_j(x, D)u\|^2 \leq C (\langle Pu, u \rangle + \|u\|^2).$$

Here  $\|u\|_s$  denotes the norm of  $u$  in the Sobolev space  $H^s$  and the notation  $\langle u, v \rangle$  denotes the  $L^2$  scalar product.

A very important point of view when it comes to the problem of the real analytic hypoellipticity is the microlocal theory for sums of squares.

First of all we note that the symbol of the commutator of two vector fields is the Poisson bracket of the symbols. Let  $X(x, D) = \sum_{j=1}^n a_j(x)D_j$ , where  $D_j = i^{-1}\partial_{x_j}$ , then the symbol of  $X$  is

$$X(x, \xi) = \sum_{j=1}^n a_j(x)\xi_j.$$

Defining the Poisson bracket of two functions  $f(x, \xi)$  and  $g(x, \xi)$  as

$$\{f, g\} = \sum_{j=1}^n (\partial_{\xi_j} f \partial_{x_j} g - \partial_{x_j} f \partial_{\xi_j} g),$$

we have that

$$\sigma([X, Y]) = \frac{1}{i} \{X(x, \xi), Y(x, \xi)\}.$$

The Hörmander Condition can then be stated microlocally. In order to do this we define first the characteristic variety of the operator  $P$  in (1.2).

**Definition 1.1.** *Let  $P$  be as in (1.2). We define the set*

$$\text{Char}(P) = \{(x, \xi) \mid (x, \xi) \in T^*\Omega \setminus \{0\}, X_j(x, \xi) = 0, \text{ for } j = 1, \dots, r\}.$$

Here  $T^*\Omega \setminus \{0\}$  denotes the cotangent bundle over  $\Omega$  minus the zero section. We point out that, unless ad hoc assumptions are made this set in general is not a manifold.

The following is the microlocal statement of Hörmander's Condition; we refer to Bolley, Camus and Nourrigat, [7], and to Fefferman and Phong, [24], for a microlocal version of the results by Hörmander and Rothschild and Stein.

**Microlocal Hörmander's Condition:**

We may suppose that, instead of having vector fields we are dealing with (real valued) pseudodifferential operators of order 1. Let  $(x_0, \xi_0) \in T^*\Omega \setminus \{0\}$ . Then there exists an iterated commutator of length  $m \geq 2$ , i.e. an operator of the form

$$\text{ad}(X_{i_1})(\text{ad}(X_{i_2}(\cdots \text{ad}(X_{i_{m-1}})(X_{i_m}) \cdots)),$$

where  $\text{ad}(X)Y = XY - YX$ , whose symbol is elliptic—i.e. non zero—at  $(x_0, \xi_0)$ .

As an example we state Hörmander theorem in a microlocal context.

**Theorem 1.3** ([7]). *Let  $a_j(x, D)$ ,  $j = 1, \dots, r$ , be real pseudodifferential operators of order 1 defined in  $\Omega$ . Let  $(x_0, \xi_0) \in T^*\Omega \setminus \{0\} \cap \text{Char}(P)$ , where  $P(x, D) = \sum_{j=1}^r a_j(x, D)^2$ . Assume further that the Microlocal Hörmander Condition holds at  $(x_0, \xi_0)$ .*

*Let  $U$  be a neighborhood of  $x_0$  in  $\Omega$  and  $u, f \in \mathcal{D}'(U)$  such that  $Pu = f$  in the distribution sense in  $U$ . Then if  $(x_0, \xi_0) \notin WF(f)$ , there is a neighborhood  $U' \subset U$  of  $x_0$  and a conic neighborhood  $\Gamma'$  of  $\xi_0$ , such that  $WF(u) \cap U' \times \Gamma' = \emptyset$ .*

## 2. THE REAL ANALYTIC CASE: A SHORT HISTORY, EXAMPLES AND COUNTEREXAMPLES

A natural question about the regularity of solutions to sums of squares is whether there is real analytic regularity provided the vector fields have real analytic coefficients and satisfy Hörmander Condition.

It is well known that in the non degenerate case, i.e. the elliptic case, the answer is in the affirmative.

The first example showing that the situation might be more involved is due to Baouendi and Goulaouic, [4], but before stating and discussing it let us introduce the definition of Gevrey class of functions.

**Definition 2.1.** *Let  $\Omega$  be an open subset of  $\mathbb{R}^n$ . We say that the function  $u \in C^\infty(\Omega)$  is in the Gevrey class  $G^s(\Omega)$ , with  $s \geq 1$ , real number, if for every compact set  $K \subset \Omega$  there is a positive constant  $C_K$  such that*

$$|\partial^\alpha u(x)| \leq C_K^{|\alpha|+1} \alpha!^s, \quad \text{for every } x \in K,$$

*and for every multiindex  $\alpha$ .*

It is straightforward that the class  $G^1(\Omega) = C^\omega(\Omega)$  i.e. it coincides with the class of all real analytic functions in  $\Omega$ .

**Theorem 2.1** ([4]). *Consider the operator in  $\mathbb{R}^3$*

$$(2.1) \quad P_{BG}(x, D_x) = D_1^2 + D_2^2 + x_1^2 D_3^2.$$

*It obviously satisfies Hörmander Condition, but there exist solutions of  $P_{BG}u = f$ , with  $f \in C^\omega(\mathbb{R}^3)$ , belonging to  $G^2$  and not to  $G^s$  with  $1 \leq s < 2$ .*

*Proof.* The proof is the construction of a suitable solution of the equation  $P_{BG}u = 0$ . Define

$$u(x) = \int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + zx_2\rho - \rho} d\rho,$$

where  $z \in \mathbb{C}$  is suitable. The integral converges provided we keep  $x_2$  in a small neighborhood of the origin. Now

$$D_1^2 u(x) = - \int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + zx_2\rho - \rho} (-\rho^2 + x_1^2\rho^4) d\rho.$$

Moreover

$$x_1^2 D_3^2 u(x) = - \int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + zx_2\rho - \rho} (-x_1^2\rho^4) d\rho$$

and finally

$$D_2^2 u(x) = - \int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + zx_2\rho - \rho} z^2 \rho^2 d\rho.$$

If we choose  $z = \pm 1$  we see that  $P_{BG}u = 0$  in a slab where  $x_2$  is in a sufficiently small neighborhood of 0. Setting  $z = 1$  then

$$u(x) = \int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + x_2\rho - \rho} d\rho.$$

Compute now  $\partial_3^k u(0)$ :

$$\partial_3^k u(0) = \int_0^{+\infty} \rho^{2k} e^{-\rho} d\rho = (2k)! = \frac{(2k)!}{k!^2} k!^2 \geq 2^k k!^2.$$

It is also easy to see that

$$\partial_2^k u(0) = k!$$

Furthermore, taking  $k$  derivatives with respect to  $x_1$  of  $u$  at zero we obtain a bunch of terms, among which the terms involving more factors

$\rho$ —responsible for a higher Gevrey regularity—are those where the  $x_1$  derivative lands on the exponential:

$$\int_0^{+\infty} e^{ix_3\rho^2 - \frac{x_1^2}{2}\rho^2 + x_2\rho - \rho} (x_1^2\rho^2)^{\frac{k}{2}} \rho^k d\rho.$$

The above quantity is bounded from above, when  $x_1$  is near 0, by  $C^{k+1}k!^{3/2}$ . This shows that  $u \in G^2$  and that its Gevrey regularity is not better than 2.  $\square$

Another example was singled out by Oleřnik, Oleřnik and Radkevič in [49], [50]. Let  $p, q$  be positive integers and consider in  $\mathbb{R}^3$  the following sum of squares

$$(2.2) \quad P_{OR}(x, \xi) = D_1^2 + x_1^{2(p-1)} D_2^2 + x_1^{2(q-1)} D_3^2,$$

where  $p < q$ . Then

**Theorem 2.2** ([49], [50], [13], [31], [20]). *The operator in (2.2) is Gevrey hypoelliptic of order  $q/p$  and this number is optimal. Moreover if we define the “partial Gevrey regularity” of a solution in the variable  $x_j$  as  $s_j$ , where  $|\partial_{x_j}^\alpha u(x)| \leq C^{\alpha+1} \alpha!^{s_j}$  for  $x$  in a compact set, we have that if  $P_{OR}u = f \in G^{q/p}$  then  $u$  has partial Gevrey regularity*

$$\left(1 + \frac{1}{p} - \frac{1}{q}, 1, \frac{q}{p}\right).$$

The above results require some discussion. The characteristic variety of the operator in (2.1) is actually a real analytic submanifold of  $T^*\mathbb{R}^3 \setminus \{0\}$  given by

$$(2.3) \quad \text{Char}(P_{BG}) = \{(x, \xi) \in T^*\mathbb{R}^3 \setminus \{0\} \mid \xi_1 = \xi_2 = x_1 = 0, \xi_3 \neq 0\}.$$

For the operator in (2.2) we have

$$(2.4) \quad \text{Char}(P_{OR}) = \{(x, \xi) \in T^*\mathbb{R}^3 \setminus \{0\} \mid \xi_1 = x_1 = 0, (\xi_2, \xi_3) \neq (0, 0)\}.$$

In the first case  $\text{Char}(P_{BG})$  has codimension 3 while in the second case  $\text{codim Char}(P_{OR}) = 2$ .

We remark that in the first case  $\text{Char}(P_{BG})$  is a non symplectic submanifold of  $T^*\mathbb{R}^3 \setminus \{0\}$ , while in the second case  $\text{Char}(P_{OR})$  is symplectic. This means that the symplectic form  $\sigma = d\xi \wedge dx$  is of maximal rank in the second case, while it has a kernel in the first case.

At the end of the seventies Tartakoff, [54], and Treves, [56], proved with different methods the following important result:

**Theorem 2.3** ([54], [56]). *Consider a sum of squares operator*

$$P(x, D) = \sum_{j=1}^r X_j(x, D)^2,$$

where the vector fields  $X_j$  have real analytic coefficients defined in an open subset  $\Omega \subset \mathbb{R}^n$  and satisfy Hörmander condition.

Assume further that

- (a) -  $\text{Char}(P)$  is a symplectic submanifold of  $T^*\mathbb{R}^n \setminus \{0\}$ .
- (b) - The principal symbol of  $P$ ,  $p(x, \xi) = \sum_{j=1}^r X_j(x, \xi)^2$  vanishes exactly to the second order on  $\text{Char}(P)$ .

Then  $P$  is analytic hypoelliptic.

We clarify briefly what the expression “vanishes exactly to the second order” means.

Denote by  $p(x, \xi)$  the (principal) symbol of  $P$  as defined above. Let  $(x_0, \xi_0) \in \text{Char}(P)$  and denote by  $Q$  the  $2n \times 2n$  matrix  $d^2p(x_0, \xi_0)$ . The Hamilton matrix of  $p$  at  $(x_0, \xi_0)$  is then defined as

$$\langle QX, Y \rangle = \sigma(X, F_p Y),$$

$\sigma$  being the symplectic form. Here  $X, Y$  are vectors in  $T_{(x_0, \xi_0)}T^*\Omega \setminus \{0\}$ .

We say that  $p(x, \xi)$  vanishes exactly to the second order at the point  $(x_0, \xi_0)$  if

$$\ker F_p(x_0, \xi_0) = T_{(x_0, \xi_0)} \text{Char}(P).$$

Let us list a few examples of operators satisfying the assumptions of the theorem.

- (a) The quadratic Grušin operator (also called the harmonic oscillator)

$$\sum_{j=1}^{n-1} (D_j^2 + x_j^2 D_n^2).$$

- (b) The Heisenberg Laplacian

$$(D_1 - x_2 D_3)^2 + (D_2 + x_1 D_3)^2.$$

- (c) The  $\square_b$  operator as well as the  $\bar{\partial}_b$  operator in the context of  $CR$ -manifolds.

We remark that the operator  $P_{BG}$  does not satisfy the assumptions of the theorem because its characteristic manifold is not symplectic since its codimension is 3. On the other hand the operator  $P_{OR}$  does not vanish exactly at the second order, even though its characteristic manifold is symplectic.

Actually the result in Theorem 2.3 can be microlocalized. The statement in [56] was already microlocal, while the statement of [54] was formulated in a microlocal way in [55].

**Theorem 2.4** ([56], [55]). *Let the same hypotheses of Theorem 2.3 be satisfied. Let  $u, f$  denote distributions for which the equation  $Pu = f$  is satisfied. Then  $WF_a(u) \subset WF_a(f)$ .*

In [56] the author, regarding the Baouendi–Goulaouic model, writes the following words:

if  $\text{Char}(P)$ , assumed to be an analytic manifold, contains a smooth curve which is orthogonal for the fundamental symplectic form to the whole tangent plane to  $\text{Char}(P)$  at every point (of the curve), the operator  $P$  might not be analytic hypo-elliptic. Actually it is my belief that, in this case,  $P$  is necessarily not so.

This is what has been later called Treves curve conjecture, even though it has not been stated like a conjecture. It should also be said that no counter examples are known and no proof has been given so far. The above statement can be rephrased by saying that if  $\text{Char}(P)$  is not symplectic, denote by  $(x_0, \xi_0)$  a point in  $\text{Char}(P)$  and assume that

$$T_{(x_0, \xi_0)} \text{Char}(P) \cap (T_{(x_0, \xi_0)} \text{Char}(P))^\sigma \neq \{0\}$$

then there is no analytic hypoellipticity. Here the notation  $E^\sigma$ , where  $E$  is a vector space, denotes the symplectic orthogonal to  $E$ .

In 1981 Métivier, in [44], proved that there is a lack of analytic hypoellipticity for the operator in  $\mathbb{R}^2$

$$(2.5) \quad P_M(x, D) = D_1^2 + (x_1^2 + x_2^2)D_2^2.$$

Let us briefly see what are the Treves' curves in this case.

We have  $\text{Char}(P_M) = \{(0, 0; 0, \xi_2), \xi_2 \neq 0\}$ . Since everything is flat we are allowed to confuse the manifold with its tangent space. Then

$$\text{Char}(P_M)^\sigma = \{(y_1, 0; \eta_1, \eta_2)\},$$

so that when we take the intersection we have

$$\text{Char}(P_M) \cap \text{Char}(P_M)^\sigma = \{0, 0; 0, \xi_2\},$$

which does not project injectively onto the base space. Hence the Treves curves are the  $\xi_2$ -lines along the fibers of the cotangent bundle.

This fact may let us surmise that the situation is very involved. We note in passing that Métivier proof of the non analytic hypoellipticity of  $P_M$  is much more difficult than that for the Baouendi–Goulaouic operator.

As a final remark of this section let us add that the case of the Oleřnik and Radkevič operator is not explained, even though, clearly, it does not vanish of exact order 2, it still has a symplectic characteristic manifold.

One can also generalize the Métivier operator as

$$(2.6) \quad M_{p,q,a}(x, D) = D_1^2 + x_1^{2(q-1)} D_2^2 + x_1^{2(p-1)} x_2^{2a} D_2^2,$$

where  $a, p, q$  are integers,  $p, q > 1$ ,  $p < q$ ,  $a > 0$ . Its characteristic variety is the real analytic submanifold

$$\text{Char}(M_{p,q,a}) = \{(0, x_2; 0, \xi_2), \xi_2 \neq 0\},$$

which is symplectic. In [12] it is proved that  $M_{p,q,a}$  is Gevrey hypoelliptic of order  $s$  for any

$$s \geq \frac{aq}{aq - q + p}.$$

When  $a = 1$ ,  $q = 2$ ,  $p = 1$  the above index gives 2, which is the value that Métivier proved to be optimal. It is worth to note that Métivier's proof is along the same lines of the proof of Theorem 2.1, but it is much more difficult. Moreover it uses the properties of the eigenfunctions of the harmonic oscillator operator in one variable. These properties are no longer true for the anharmonic oscillator:  $D_t^2 + t^{2(q-1)}$  (see [28] for a proof of this fact.)

As a consequence there is no proof of the optimality of the above index for  $M_{p,q,a}$ , except for particular values of  $p, q$ , that is when  $q-1 = 2k+1$  and  $p-1 = k$ . See Chinni, [18], for such a proof using the result [5], by Bender and Wang.

### 3. GEOMETRY OF THE CHARACTERISTIC VARIETY: STRATIFICATIONS AND THE TREVES CONJECTURE

In 1996, see the paper [58], F. Trèves came up with a new idea for the study of the analytic hypoellipticity of sums of squares. In this section we are going to give a fairly precise description of his idea, because it is important for what follows.

Stimulated by the papers [30], [31] by N. Hanges and A. A. Himonas, who proved that the Oleřnik and Radkevič operator for special values of  $p$  and  $q$ , is not analytic hypoelliptic, even though its characteristic manifold is a real analytic symplectic submanifold, F. Trèves introduced the idea that in order to establish if there is analytic hypoellipticity or not one has to look at the strata of a stratification of the characteristic variety.

Hence he proposed a certain stratification that will be henceforth called the Poisson stratification and formulated the conjecture that an operator is analytic hypoelliptic if and only if all the strata in the stratification of its characteristic variety are symplectic real analytic submanifolds.

We now give a detailed description of the Poisson stratification as well as some examples. We shall follow the presentation in the paper [15].

Denote  $\Sigma$  the variety  $\text{Char}(P)$ , where the symbols of all the vector fields are zero.

First of all let us define what we mean by the term stratification.

**Definition 3.1** (see e.g. [60]). *By an analytic stratification of  $\Sigma$  in  $T^*\mathbb{R}^n \setminus \{0\}$  we mean a partition of  $\Sigma$*

$$\Sigma = \bigcup_{i \in I} S_i,$$

where the  $S_i$  are connected analytic submanifolds of  $T^*\mathbb{R}^n \setminus \{0\}$  satisfying the conditions

- (i) *Every compact subset of  $T^*\mathbb{R}^n \setminus \{0\}$  intersects at most finitely many submanifolds  $S_i$ .*
- (ii) *For any  $i, i'$  belonging to the index family  $I$ ,  $S_{i'} \cap \overline{S_i} \neq \emptyset$  implies  $S_{i'} \subset \partial S_i$  and  $\dim S_{i'} < \dim S_i$ .*

The next is the definition of a (micro)local stratification. The definition is given in general terms, the adaptation to the homogeneous-on-the-fibers situation is straightforward.

**Definition 3.2** ([60]). *By a local analytic stratification of  $\Sigma$  we mean a system  $(U, \{S_i\}_{i \in I})$ , where  $U$  is an open set in  $T^*\mathbb{R}^n \setminus \{0\}$ ,  $I$  is a finite index family,  $S_i$  is a connected analytic submanifold of  $U$  satisfying condition (ii) above and such that*

$$\Sigma \cap U = \bigcup_{i \in I} S_i.$$

Next we are going to describe how to construct a local analytic stratification. This can be accomplished in several ways, however we stick to the description of [15] to keep the content the least abstract and the most readable.

**3.1. The analytic stratification.** Let us denote by

$$X(x, \xi) = (X_1(x, \xi), \dots, X_r(x, \xi))$$

the map whose components are the symbols of the vector fields. Moreover let  $\Sigma = X^{-1}(0) \cap T^*\Omega \setminus \{0\}$  the characteristic variety. Note

that, since our maps are real valued, we might have used the function  $p(x, \xi) = \sum_{j=1}^r X_j(x, \xi)^2$  to define  $\Sigma$ , but since in the following steps the minors of the Jacobian matrix of  $X$  are going to play a role, keeping the consistency of the notation would have been much more complicated. Thus we stick to the vector notation.

Define  $\mathfrak{R}_0(\Sigma)$  as the subset of  $\Sigma$  whose points  $z_0 = (x_0, \xi_0)$  have a neighborhood  $U_{z_0} \subset V$ ,  $V$  open subset of  $T^*\Omega \setminus \{0\}$ , such that there are indices  $j_\alpha$ ,  $\alpha = 1, \dots, m$ ,  $1 \leq j_1 < \dots < j_m \leq r$ , for which

$$U_{z_0} \cap \Sigma = \{z \in U_{z_0} \mid X_{j_\alpha}(x, \xi) = 0, \alpha = 1, \dots, m\},$$

and the differentials  $dX_{j_\alpha}(z_0)$  are all linearly independent. The latter is equivalent to saying that the minor

$$\frac{\partial(X_{j_1}, \dots, X_{j_m})}{\partial(z_{i_1}, \dots, z_{i_m})}(z_0),$$

where  $1 \leq i_1 < \dots < i_m \leq 2n$ , is non zero. It is evident that  $\mathfrak{R}_0(\Sigma)$  is a  $C^\omega$  manifold of codimension  $m$ .

Next we define two subsets of  $\Sigma$ ,  $\Sigma_1$  and  $\Sigma_2$ . Let  $\Sigma_1$  denote the subset of  $\Sigma$  in which all the  $m \times m$  minors of the matrix  $\frac{\partial X}{\partial z}$  vanish identically.

Define  $\Sigma_2$  as the zero set in  $V \setminus (\Sigma_1 \cup \mathfrak{R}_0(\Sigma))$  of all the  $(m+1) \times (m+1)$  minors

$$\frac{\partial(X_{j_1}, \dots, X_{j_{m+1}})}{\partial(z_{i_1}, \dots, z_{i_{m+1}})},$$

$1 \leq i_1 < \dots < i_{m+1} \leq 2n$ .

We may now iterate for  $\Sigma_1$ ,  $\Sigma_2$  what has been done for  $\Sigma$ . For  $\Sigma_1$  define the map

$$X^{(1)}(x, \xi) = (X(x, \xi), X_{i_1, \dots, i_m}^{j_1, \dots, j_m}) : V \rightarrow \mathbb{R}^{r_1, 1}$$

with  $X_{i_1, \dots, i_m}^{j_1, \dots, j_m}$  denoting the  $m \times m$  minors and  $r_{1,1} = r + r_1$ ,  $r_1$  being the number of the  $m \times m$  minors.

Analogously define

$$X^{(2)}(x, \xi) = (X(x, \xi), X_{i_1, \dots, i_{m+1}}^{j_1, \dots, j_{m+1}}) : V \rightarrow \mathbb{R}^{r_1, 2}$$

with  $X_{i_1, \dots, i_{m+1}}^{j_1, \dots, j_{m+1}}$  denoting the  $(m+1) \times (m+1)$  minors and  $r_{1,2} = r + r_2$ ,  $r_2$  being the number of the  $(m+1) \times (m+1)$  minors.

This leads to a local stratification of  $\Sigma$ : if  $V$  is a neighborhood of  $z_0$  with a compact closure then

$$(3.1) \quad V \cap \Sigma = \bigcap_{\alpha=0}^{N_\Omega} \Lambda_\alpha,$$

where the  $\Lambda_\alpha$  are  $C^\omega$  manifolds. The  $\Lambda_\alpha$  shall be called the analytic strata of  $\Sigma$ .

**Example 1** (The Whitney umbrella). *This example is not on a cotangent bundle. Let  $\Sigma = \{x \in \mathbb{R}^3 \mid x_1^2 - x_3x_2^2 = 0\}$ .  $\mathfrak{R}_0(\Sigma) = \{x \in \mathbb{R}^3 \mid x_1^2 - x_3x_2^2 = 0, x_1^2 + x_2^2 > 0\}$ .*

*Then  $X^{(1)}(x) = (x_1^2 - x_3x_2^2, x_1, x_2x_3, x_2^2)$ . Its differential is*

$$\begin{bmatrix} 2x_1 & -2x_2x_3 & -x_2^2 \\ 1 & 0 & 0 \\ 0 & x_3 & x_2 \\ 0 & 2x_2 & 0 \end{bmatrix}.$$

*Its restriction to  $\Sigma_1$  has rank 2 if  $x_3 \neq 0$  and rank 1 at the origin. The analytic stratification of  $\Sigma$  is composed of 5 strata.*

**3.2. The symplectic stratification.** Assuming we already have a stratified variety of the form (3.1), we denote by  $\Sigma$  one of the strata  $\Lambda_\alpha$  in (3.1), i.e. a connected  $C^\omega$  submanifold defined near a point  $z_0 \in \text{Char}(P)$ , and let  $\sigma$  be the symplectic form in  $\mathbb{R}^{2n}$ .

Then there are functions  $G_j(x, \xi)$ ,  $j = 1, \dots, s$ , and an open set  $\Omega' \subset \Omega$  such that  $\Sigma \cap \Omega' = \{z \in \Omega' \mid G_j(z) = 0, j = 1, \dots, s\}$ . Moreover we may assume that the rank of the map  $G = (G_1, \dots, G_s)$  is equal to  $\text{codim } \Sigma$  at each point of  $\Sigma \cap \Omega'$ . Thus if  $d = \text{codim } \Sigma$ , each  $z_0 \in \Sigma$  has a neighborhood  $U_{z_0} \subset \Omega'$  in which there are indices  $1 \leq i_1 < \dots < i_d \leq s$  such that

- (i) The differentials  $dG_{i_k}(z_0)$  are linearly independent.
- (ii)  $\Sigma \cap U_{z_0} = \{z \in U_{z_0} \mid G_{i_1}(z) = \dots = G_{i_d}(z) = 0\}$ .

Consider the pull back of  $\sigma$  to  $\Sigma$  and denote it by  $\sigma|_\Sigma$ . Let  $\sigma_{z|\Sigma}$ ,  $z \in \Sigma$ , denote the restriction of the symplectic form to  $T_z\Sigma$ . The rank of the linear map corresponding to the skew symmetric bilinear form  $\sigma_{z|\Sigma}$  is called the rank of the symplectic form on  $\Sigma$  at the point  $z$  or the symplectic rank of  $\Sigma$  at the point  $z$ .

Denote by  $\mu$  the maximum rank of  $\Sigma$ . Then the set  $\Sigma_0$  of all the points  $z$  where the symplectic rank is equal to  $\mu$  is a dense subset of  $\Sigma$ . Each connected component of  $\Sigma_0$  is a  $C^\omega$  submanifold of  $U_{z_0}$  whose symplectic rank at every point is equal to  $\mu$ .

The subset  $\Sigma \setminus \Sigma_0$  is an analytic variety that can be defined by the vanishing of the functions  $G_1, \dots, G_s$ , as well as of all the  $\nu \times \nu$  minors of the matrix  $[\{G_i, G_j\}]_{1 \leq i, j \leq s}$ , where  $\nu = \mu + \text{codim } \Sigma - \dim \Sigma$ . Hence we can find an analytic stratification of this subset and the dimension of each analytic stratum of  $\Sigma \setminus \Sigma_0$  is strictly less than the dimension of  $\Sigma_0 = \dim \Sigma$ .

This implies that we can decompose  $\Sigma$  so that

$$\Sigma \cap U = \bigcup_{\alpha=1}^{N_U} \Sigma_\alpha,$$

where each  $\Sigma_\alpha$  is a connected  $C^\omega$  submanifold with a constant symplectic rank.

**3.3. The Poisson stratification.** Again we start with the analytic set  $\Sigma = \text{Char}(P)$ . For each multiindex  $I = (i_1, \dots, i_\nu)$ ,  $\nu \in \mathbb{N}$ , we define

$$X_I(x, \xi) = \{X_{i_1}, \{X_{i_2}, \{\dots \{X_{i_{\nu-1}}, X_{i_\nu}\} \dots\}\}(x, \xi),$$

if  $\nu \geq 2$  and  $X_I = X_{i_1}$ , if  $I = (i_1)$ . We also set  $|I| = \nu$ . Here  $\{f, g\}$  denotes the Poisson bracket of the functions  $f$  and  $g$ :

$$\{f, g\}(x, \xi) = \sum_{j=1}^n \left( \frac{\partial f}{\partial \xi_j} \frac{\partial g}{\partial x_j} - \frac{\partial f}{\partial x_j} \frac{\partial g}{\partial \xi_j} \right) (x, \xi).$$

Of course we *are assuming* that the vector fields  $X_i$  satisfy the microlocal Hörmander condition, i.e. that for every  $(x, \xi) \in \text{Char}(P)$  there exists a multiindex  $I$  such that  $X_I(x, \xi) \neq 0$ .

Let now  $U$  be a neighborhood of a point  $z_0 = (x_0, \xi_0)$  and write as before  $\Sigma = \text{Char}(P)$ . Then we may define a sequence of analytic subsets of  $U$  as

$$\Sigma^{(\nu)} = \{z \in U \mid \text{for every multiindex } I, |I| \leq \nu, X_I(z) = 0\}.$$

We point out that the sequence  $\Sigma^{(\nu)}$  is non increasing in  $\nu$  and that in particular  $\Sigma^{(1)} = \Sigma$ . Furthermore, by the Hörmander condition, we have that

$$\bigcap_{\nu=1}^{\infty} \Sigma^{(\nu)} = \emptyset.$$

Now there is an increasing sequence of integers  $1 = \nu_1 < \nu_2 < \dots$  such that

- (i)  $\Sigma^{(\nu_{p+1})} \subsetneq \Sigma^{(\nu_p)}$ .
- (ii) If  $\nu_p < \nu_{p+1}$ , then  $\Sigma^{(\nu')} = \Sigma^{(\nu_p)}$ , for every  $\nu'$ ,  $\nu_p \leq \nu' < \nu_{p+1}$ .

Consider now for any integer  $p$  the symplectic stratification (in the open set  $U$ ) of the analytic set  $\Sigma^{(\nu_p)}$ :

$$\Sigma^{(\nu_p)} = \bigcup_{\alpha=1}^{N_U} \Sigma_\alpha^{(\nu_p)}.$$

In each stratum  $\Sigma_\alpha^{(\nu_p)}$  the set of points  $z \in \Sigma^{(\nu_p)} \setminus \Sigma^{(\nu_{p+1})}$  is either empty or else an open and dense subset of  $\Sigma_\alpha^{(\nu_p)}$ . If it is not empty, denote by  $\Sigma_{\alpha,\beta}^{(\nu_p)}$  its connected components. Thus we get the decomposition

$$\Sigma^{(\nu_p)} = \Sigma^{(\nu_{p+1})} \cup \bigcup_{\alpha=1}^{N_U} \bigcup_{\beta=1}^{M_U} \Sigma_{\alpha,\beta}^{(\nu_p)}.$$

Finally, letting  $p$  run over the integers we obtain a decomposition of the form

$$(3.2) \quad \Sigma = \bigcup_p \bigcup_j \Sigma_j^{(\nu_p)},$$

where  $p, j$  have a finite range (in the open set  $U$ ) and

- (i) The  $C^\omega$  manifolds  $\Sigma_j^{(\nu_p)}$  are connected and pairwise disjoint.
- (ii) The symplectic rank of  $\Sigma_j^{(\nu_p)}$  is constant.
- (iii) At every point of  $\Sigma_j^{(\nu_p)}$  the Poisson brackets  $X_I$ , with  $|I| < \nu_{p+1}$  vanish, but there is at least one bracket  $X_I$  with  $|I| = \nu_{p+1}$  which does not vanish.

We may then give the following

**Definition 3.3.** *The partition (3.2) of  $\text{Char}(P) = \Sigma$  is called the (local) Poisson stratification corresponding to the vector fields  $X_1, \dots, X_r$ . Each submanifold  $\Sigma_j^{(\nu_p)}$  is a Poisson stratum, or simply just a stratum, for  $\Sigma$ . We refer to the integer  $\nu_p$  as the depth of the stratum  $\Sigma_j^{(\nu_p)}$ .*

**Remark 3.1.** *It follows immediately from the definition above that the stratification of  $\Sigma$  defined by the vector fields  $X_j$ ,  $j = 1, \dots, r$ , is invariant under nonsingular  $C^\omega$  linear substitutions, that means if we define*

$$\tilde{X}_j(x, \xi) = \sum_{k=1}^r a_{jk}(x, \xi) X_k(x, \xi),$$

for  $j = 1, \dots, r$ , we obtain the same stratification.

Assume that a stratum, say  $\Sigma'$ , of the stratification (3.2) is not symplectic. Since the symplectic rank is constant we have that  $\Sigma'$  is foliated by  $C^\omega$  submanifolds whose tangent space is isomorphic to  $T_z \Sigma' \cap (T_z \Sigma')^\sigma$ . We call these submanifolds the Hamilton leaves of the stratification. If  $\text{Char}(P)$  is a real analytic manifold and the symplectic form has constant rank on each connected component of  $\text{Char}(P)$ , then there are curves (contained in the Hamilton leaves) satisfying the assumptions of the Treves curve conjecture.

It is also clear that the latter situation may occur at a deeper stratum.

We may then state the

**Conjecture 3.1** (Treves conjecture, [58], [59], [15]). *The operator  $P$  is analytic hypoelliptic if and only if each stratum in its Poisson stratification is (microlocally) a symplectic  $C^\omega$  submanifold.*

There are also other notions of analytic hypoellipticity, like global analytic hypoellipticity and germ analytic hypoellipticity. Moreover one might be interested in the analytic singular support of the solution, i.e. just the local theory. In this paper we stick to the microlocal point of view, since we think that it is the most basic and refer to the paper [59] for further details about the formulation of the conjecture in different, albeit related, situations.

#### 4. EXAMPLES AND COUNTEREXAMPLES

In this section we discuss some model operators and examine their Poisson stratification as well as—when known—their hypoellipticity properties.

**4.1. Examples.** Consider the operator in (2.2), with  $1 < p < q$ . Then

$$\text{Char}(P_{OR}) = \{(0, x_2, x_3; 0, \xi_2, \xi_3) \mid \xi_2^2 + \xi_3^2 > 0\}.$$

This is obviously a symplectic submanifold, so that the rank of the symplectic form restricted to  $\text{Char}(P_{OR})$  is constant and equal to 4.

As we said in Section 2, Theorem 2.2 holds, showing that it is not analytic hypoelliptic.

First of all this shows that the mere analytic and symplectic stratifications are not enough to imply analytic hypoellipticity.

The first Poisson strata are then

$$\Sigma_{1,\pm} = \{(x, \xi) \mid \xi_1 = x_1 = 0, \xi_2 \gtrless 0\}.$$

Points in  $\Sigma_{1,\pm}$  are characteristic points and all Poisson brackets of length  $k + 1$  of the form  $\text{ad}(X_1)^k X_j$  are zero for  $k < p - 1$ . It is evident that  $X_1$  is the only field contributing to this computation since both  $X_2$  and  $X_3$  carry vanishing coefficients.

When we take brackets of length  $p$  we have that

$$\text{ad}(X_1)^{p-1} X_2 = (p - 1)! \xi_2.$$

This is zero if  $\xi_2 = 0$ , which is possible, provided  $\xi_3 \neq 0$ . Hence the strata of depth  $p$  are

$$\Sigma_{p,\pm} = \{(x, \xi) \mid \xi_1 = x_1 = 0 = \xi_2, \xi_3 \gtrless 0\}.$$

The latter is not symplectic since it has codimension 3. Note that the Baouendi–Goulaouic model is obtained for  $p = 1$ .

As a second example let us consider the operator

$$(4.1) \quad D_1^2 + \sum_{j=1}^N (p_j(x) D_2)^2, \quad x \in \mathbb{R}^2,$$

where the polynomials  $p_j$  satisfy

$$(4.2) \quad p_j(\lambda x_1, \lambda^\theta x_2) = \lambda^{m_j} p_j(x_1, x_2), \quad \lambda > 0,$$

$\theta, m_j$  being positive rational numbers. We may always assume that the labeling of the polynomials is such that

$$m_1 \leq m_2 \leq \cdots \leq m_N.$$

Then

**Theorem 4.1** ([14]). *Consider the operator in (4.1). Suppose that for a number  $r$ ,  $1 \leq r \leq N$ , we have*

$$p_r(1, 0) \neq 0, \quad p_j(1, 0) = 0, \quad \text{for } j < r.$$

Write

$$p_j(x) = \sum_{k=0}^{m_j} \alpha_{jk} x_1^k x_2^{q_{jk}},$$

where the  $q_{jk}$  are non-negative integers,  $q_{jm_j} = 0$ , and otherwise  $q_{jk} \geq 1$ .

Then the operator in (4.1) is  $G^s$  hypoelliptic for

$$s \geq \frac{1}{1 - \lambda},$$

where

$$\lambda = \frac{\theta}{m_r + 1} \max_{1 \leq j \leq r} \max_{\substack{0 \leq k < m_j \\ \alpha_{jk} \neq 0}} \frac{m_r - k}{m_j - k}.$$

Let us examine the stratification of (4.1). We consider only the case when  $N = 1$ ; the more general case is quite similar. Thus let

$$P(x, D) = D_1^2 + (p(x) D_2)^2.$$

Since we are assuming that  $P$  satisfies Hörmander condition, we may assume, after application of Weierstraß preparation theorem, dropping for simplicity the non zero factor, that  $p$  has the form

$$p(x) = x_1^m + \sum_{k=0}^{m-1} \alpha_k x_1^k x_2^{q_k},$$

where the  $q_k$  are non negative integers such that the homogeneity hypothesis is satisfied.

The characteristic variety is then given by

$$\xi_1 = 0, p(x) = 0.$$

The zero set of  $p$  will be considered in more detail in Section 5. We mention here only the basic things necessary to understand the problem. One can show that  $p^{-1}(0)$  has at most a finite number of branch points and in the complement of those points it is a  $C^\omega$  submanifold of  $\mathbb{R}^2$ . Because of Hörmander condition we obtain that the characteristic variety is a symplectic submanifold of  $T^*\mathbb{R}^2 \setminus \{0\}$  in the complement of the branch points.

Hence the stratification is essentially a stratification in the  $x$ -space of the form

$$\text{Char}(P) = \bigcup_{i=1}^L M_i \cup \bigcup_{j=1}^{L_1} \{\rho_j\},$$

where

$$M_i = \{(x, \xi) \mid \xi_1 = 0, \xi_2 \neq 0, x \in \tilde{M}_i\},$$

$\tilde{M}_i$  denoting the  $C^\omega$  connected components of  $p^{-1}(0)$ , while

$$\rho_j = (\tilde{\rho}_j; 0, \xi_2 \neq 0),$$

where the  $\tilde{\rho}_j$  are the branch points in  $p^{-1}(0)$ .

In this case the only non symplectic strata are lines parallel to the fibers of the cotangent bundle and projecting onto a single point on the base space.

We point out that Theorem 4.1 gives Gevrey regularity that are known to be optimal only in particular cases, e.g. the Métivier operator, see (2.5). The optimality for a generic operator of that form is not proved.

Likewise the analog of Theorem 4.1 in a non homogenous case is not known. Proving optimality in a non homogenous case would amount to prove that Conjecture 3.1 holds true in two variables.

**4.2. Counterexamples.** Let  $r, p, q \in \mathbb{N}$ ,  $1 < r < p < q$ , and  $x \in \mathbb{R}^4$ . Consider the operator

$$(4.3) \quad P_1(x, D) = D_1^2 + D_2^2 + x_1^{2(r-1)} (D_3^2 + D_4^2) + x_2^{2(p-1)} D_3^2 + x_2^{2(q-1)} D_4^2.$$

Evidently  $P_1$  is a sum of squares operator verifying Hörmander condition, since  $\text{ad}(D_1)^{r-1} x_1^{r-1} D_i$  yields  $D_i$ ,  $i = 3, 4$ .

The characteristic variety of  $P_1$  is

$$\text{Char}(P_1) = \{(x, \xi) \mid \xi_1 = \xi_2 = 0, x_1 = x_2 = 0, \xi_3^2 + \xi_4^2 > 0\}.$$

The stratification associated with  $P_1$  is made up of a symplectic single stratum

$$\Sigma_1 = \{(0, 0, x_3, x_4; 0, 0, \xi_3, \xi_4) \mid \xi_3^2 + \xi_4^2 > 0\} = \text{Char}(P_1).$$

Then we have

**Theorem 4.2** ([3]). *Let*

$$\frac{1}{s_0} = \frac{1}{r} + \frac{r-1}{r} \frac{p-1}{q-1}.$$

*Then  $P_1$  in a neighborhood of the origin is locally Gevrey  $s_0$  hypoelliptic and not better.*

It is not difficult to show that Theorem 4.2 implies the following

**Corollary 4.1.** *The sufficient part of the Conjecture 3.1 does not hold in dimension  $n$  for  $n \geq 4$ .*

Next we give a sketchy idea of the proof of Theorem 4.2, since, in our opinion, it may help getting an idea about where and why analytic regularity fails in this model.

**Idea of the proof of Theorem 4.2.** First of all we note that the Hörmander hypothesis is satisfied at order  $r$ , meaning that the whole 4-dimensional Lie algebra is generated by taking iterated commutators of length at most  $r$ .

Using the subelliptic inequality it is not difficult to show that a distribution solution of  $P_1 u = f$ , with  $f$  real analytic is in  $G^{s_0}$  near a characteristic point.

Hence we focus on the converse statement: There is a real analytic function  $f$  and a  $G^{s_0}$  function,  $u$ , such that  $P_1 u = f$  and moreover  $u$  is not better than  $G^{s_0}$ . To this end we must construct such a function  $u$ , basically doing the same as in Theorem 2.1, i.e. constructing some sort of inverse Fourier transform whose exponential decay at infinity prevents analyticity. Of course both the (complex) phase and the amplitude are more involved in this case. In particular the amplitude is obtained by studying the semiclassical eigenfunctions and eigenvalues of a certain Schrödinger operator with a double well potential with non degenerate minima blowing up at infinity.

We follow the proof in [3]. We look for a function  $u$  such that

$$P_1(x, D)A(u) = 0,$$

where

$$(4.4) \quad A(u)(x) = \int_{M_u}^{+\infty} e^{-i\rho x_4 + x_3 z(\rho)\rho^\theta - \rho^\theta} u(\rho^{\frac{1}{r}} x_1, \rho^\mu x_2, \rho) d\rho.$$

Here  $\theta = s_0^{-1}$ ,  $\mu > 0$ ,  $z(\rho)$  and  $M_u > 0$  are to be determined. We assume that  $x$  is in a suitable neighborhood of the origin whose size will ultimately depend on the upper estimate for  $z(\rho)$ .

Applying  $P_1$  to  $A(u)$  we obtain

$$\begin{aligned} P_1(x, D)A(u)(x) &= \int_{M_u}^{+\infty} e^{-i\rho x_4 + x_3 z(\rho)\rho^\theta - \rho^\theta} \left[ -\rho^{\frac{2}{r}} \partial_{x_1}^2 u - x_1^{2(r-1)} (z(\rho))^2 \rho^{2\theta} u \right. \\ &\quad \left. + x_1^{2(r-1)} \rho^2 u - \rho^{2\mu} \partial_{x_2}^2 u - x_2^{2(p-1)} (z(\rho))^2 \rho^{2\theta} u + x_2^{2(q-1)} \rho^2 u \right] d\rho, \end{aligned}$$

which, in terms of the variables  $y_1 = \rho^{\frac{1}{r}} x_1$ ,  $y_2 = \rho^\mu x_2$ , becomes

$$\begin{aligned} P_1(x, D)A(u)(x) &= \int_{M_u}^{+\infty} e^{-i\rho x_4 + x_3 z(\rho)\rho^\theta - \rho^\theta} \left[ -\rho^{\frac{2}{r}} \partial_1^2 u - y_1^{2(r-1)} (z(\rho))^2 \rho^{2\theta - 2\frac{r-1}{r}} u \right. \\ &\quad \left. + y_1^{2(r-1)} \rho^{2 - 2\frac{r-1}{r}} u - \rho^{2\mu} \partial_2^2 u - y_2^{2(p-1)} (z(\rho))^2 \rho^{2\theta - 2(p-1)\mu} u \right. \\ &\quad \left. + y_2^{2(q-1)} \rho^{2 - 2(q-1)\mu} u \right]_{\substack{y_1 = \rho^{1/r} x_1 \\ y_2 = \rho^\mu x_2}} d\rho. \end{aligned}$$

Choose  $\mu = \frac{1}{q}$ . Then

$$\begin{aligned} P_1(x, D)A(u)(x) &= \int_{M_u}^{+\infty} e^{-i\rho x_4 + x_3 z(\rho)\rho^\theta - \rho^\theta} \left[ -\rho^{\frac{2}{r}} \left( \partial_1^2 - y_1^{2(r-1)} (1 - (z(\rho))^2 \rho^{2(\theta-1)}) \right) u \right. \\ &\quad \left. + \rho^{\frac{2}{q}} \left( -\partial_2^2 - y_2^{2(p-1)} (z(\rho))^2 \rho^{2\theta - 2\frac{p}{q}} + y_2^{2(q-1)} \right) u \right]_{\substack{y_1 = \rho^{1/r} x_1 \\ y_2 = \rho^{\frac{1}{q}} x_2}} d\rho. \end{aligned}$$

We point out that  $\theta - 1 < 0$ . Make the Ansatz  $|z(\rho)| < M_u^{1-\theta}$  and set  $\tau(\rho) = (1 - (z(\rho))^2 \rho^{2(\theta-1)})^{\frac{1}{2r}}$ .

Choosing  $u(y_1, y_2, \rho) = u_1(\tau(\rho)y_1)u_2(y_2, \rho)$ , where

$$(4.5) \quad \left( -\partial_1^2 + y_1^{2(r-1)} \tau(\rho)^{2r} \right) u_1(\tau(\rho)y_1) = \tau(\rho)^2 \lambda u_1(\tau(\rho)y_1),$$

and  $\lambda > 0$  is such that, for fixed  $\rho > 0$ , the factor in front of  $u_1$  in the r.h.s. of the above equation is in the spectrum of the quantum anharmonic oscillator  $\left( -\partial_1^2 + y_1^{2(r-1)} (1 - (z(\rho))^2 \rho^{2(\theta-1)}) \right)$ , whose frequency

depends on both  $\rho$  and  $z(\rho)$ . Then

$$\begin{aligned} & P_1(x, D)A(u)(x) \\ &= \int_{M_u}^{+\infty} e^{-i\rho x_4 + x_3 z(\rho)\rho^\theta - \rho^\theta} u_1(\tau(\rho)\rho^{\frac{1}{r}}x_1) \left[ \left\{ \rho^{\frac{2}{r}} (1 - (z(\rho))^2 \rho^{2(\theta-1)})^{\frac{1}{r}} \lambda \right. \right. \\ & \quad \left. \left. + \rho^{\frac{2}{q}} \left( -\partial_2^2 - y_2^{2(p-1)} (z(\rho))^2 \rho^{2\theta-2\frac{p}{q}} + y_2^{2(q-1)} \right) \right\} u_2(y_2, \rho) \right]_{y_2=\rho^{\frac{1}{q}}x_2} d\rho. \end{aligned}$$

Next we want to find  $u_2$  as a solution to the differential equation

$$(4.6) \quad \begin{aligned} & (1 - (z(\rho))^2 \rho^{2(\theta-1)})^{\frac{1}{r}} \lambda u_2 \\ & \quad + \rho^{\frac{2}{q} - \frac{2}{r}} \left( -\partial_2^2 - y_2^{2(p-1)} (z(\rho))^2 \rho^{2\theta-2\frac{p}{q}} + y_2^{2(q-1)} \right) u_2 = 0. \end{aligned}$$

(4.6) above then may be written

$$\begin{aligned} & (1 - (z(\rho))^2 \rho^{2(\theta-1)})^{\frac{1}{r}} \lambda u_2 \\ & \quad + \rho^{\frac{2}{q} - \frac{2}{r}} \left( -\partial_2^2 + y_2^{2(q-1)} \right) u_2 - (z(\rho))^2 \rho^{2\left(\theta - \frac{p-1}{q} - \frac{1}{r}\right)} y_2^{2(p-1)} u_2 = 0. \end{aligned}$$

Since

$$\theta - \frac{p-1}{q} - \frac{1}{r} = \left( \frac{1}{q} - \frac{1}{r} \right) \frac{p-1}{q-1},$$

we set

$$(4.7) \quad t = \rho^{\frac{1}{q} - \frac{1}{r}},$$

so that the above equation becomes

$$\begin{aligned} & \left( 1 - (z_1(t))^2 t^{2(r-1)\frac{q}{q-1} - \frac{q-p}{q-r}} \right)^{\frac{1}{r}} \lambda u_2 \\ & \quad + t^2 \left( -\partial_2^2 + y_2^{2(q-1)} \right) u_2 - (z_1(t))^2 t^{2\frac{p-1}{q-1}} y_2^{2(p-1)} u_2 = 0, \end{aligned}$$

where  $z_1(t) = z(\rho)$ . The latter equation can be turned into a stationary semiclassical Schrödinger equation if we perform the canonical dilation

$$y_2 = yt^{-\frac{1}{q-1}} :$$

$$\begin{aligned} & \left( 1 - (z_1(t))^2 t^{2(r-1)\frac{q}{q-1} - \frac{q-p}{q-r}} \right)^{\frac{1}{r}} \lambda u_2 \\ & \quad - t^{2\frac{q}{q-1}} \partial_y^2 u_2 + y^{2(q-1)} u_2 - (z_1(t))^2 y^{2(p-1)} u_2 = 0. \end{aligned}$$

Set

$$(4.8) \quad h = t^{\frac{q}{q-1}}.$$

Note that  $t, h$  are small and positive for large  $\rho$ . Thus we may rewrite the above equation as

$$(4.9) \quad \left[ \left( 1 - (z_2(h))^2 h^{2(r-1)\frac{q-p}{q-r}} \right)^{\frac{1}{r}} \lambda - h^2 \partial_y^2 + y^{2(q-1)} - (z_2(h))^2 y^{2(p-1)} \right] u_2 = 0,$$

where  $z_2(h) = z_1(t)$ . One can show that there are countably many choices for the function  $z_2(h)$  in such a way that equation (4.9) has a non zero solution in  $L^2(\mathbb{R})$ , which is a smooth rapidly decreasing function.

First observe that the operator

$$-h^2 \partial_y^2 + y^{2(q-1)} - (z_2(h))^2 y^{2(p-1)},$$

is a Schrödinger operator with a symmetric double well potential which is not positive. We obtain a positive potential just adding its minimum

$$\hat{\gamma} z_2^{\frac{2q-1}{q-p}},$$

where

$$\hat{\gamma} = -\frac{q-p}{q-1} \left( \frac{p-1}{q-1} \right)^{\frac{p-1}{q-p}} < 0.$$

Equation (4.9) becomes

$$(4.10) \quad \left[ \left( 1 - (z_2(h))^2 h^{2(r-1)\frac{q-p}{q-r}} \right)^{\frac{1}{r}} \lambda + \hat{\gamma} z_2(h)^{\frac{2q-1}{q-p}} - h^2 \partial_y^2 + y^{2(q-1)} - (z_2(h))^2 y^{2(p-1)} - \hat{\gamma} z_2(h)^{\frac{2q-1}{q-p}} \right] u = 0.$$

Performing the canonical dilation  $x \rightarrow x z_2^{\frac{1}{q-p}}$ —we make here the Ansatz that  $z_2$  is positive—(4.9) becomes

$$(4.11) \quad \left[ \left( 1 - (z_2(h))^2 h^{2(r-1)\frac{q-p}{q-r}} \right)^{\frac{1}{r}} z_2(h)^{-2\frac{q-1}{q-p}} \lambda + \hat{\gamma} - h^2 z_2(h)^{-\frac{2q}{q-p}} \partial_x^2 + x^{2(q-1)} - x^{2(p-1)} - \hat{\gamma} \right] u = 0.$$

By [6] the operator in the second line above has a discrete simple spectrum depending in a real analytic way on the parameter  $h z_2(h)^{-\frac{q}{q-p}}$ , for  $h > 0$ . Let

$$E \left( \frac{h}{z_2(h)^{\frac{q}{q-p}}} \right)$$

be one of its eigenvalues and  $u = u(x, h)$  the corresponding eigenfunction. Equation (4.11) then becomes a scalar equation

$$(4.12) \quad \left(1 - (z_2(h))^2 h^{2(r-1)\frac{q-p}{q-r}}\right)^{\frac{1}{r}} z_2(h)^{-2\frac{q-1}{q-p}\lambda + \hat{\gamma} + E} \left(\frac{h}{z_2(h)^{\frac{q}{q-p}}}\right) = 0.$$

To solve the above equation, one proves that the function  $z_2$  exists and is defined on a certain domain near the origin:

**Proposition 4.1** ([3]). *There is  $h_0 > 0$  such that equation (4.12) implicitly defines a function  $z_2 \in C([0, h_0[) \cap C^\omega(]0, h_0[)$ . In particular*

$$z_2(h) \rightarrow \tilde{z} = \left(-\frac{\lambda}{\hat{\gamma}}\right)^{\frac{q-p}{2(q-1)}} > 0$$

when  $h \rightarrow 0+$ . Therefore we may always assume that

$$(4.13) \quad z_2(h) \in \left[\frac{1}{2}\tilde{z}, \frac{3}{2}\tilde{z}\right],$$

for  $h \in [0, h_0[$ .

Let  $h_0$  be the quantity define in Proposition 4.1. Set  $h_0 = \rho_0^{\left(\frac{1}{q} - \frac{1}{r}\right)\frac{q}{q-1}}$ . Choosing  $M_u \geq \max\{\rho_0, (\frac{3}{2}\tilde{z})^{\frac{1}{1-\theta}}\}$  we have that the function  $z_2$  is defined for  $\rho \geq M_u$  and that  $|z(\rho)| < M_u^{1-\theta}$  is satisfied, so that  $1 - z(\rho)^2 \rho^{2(\theta-1)} > 0$ .

Using some *a priori* estimate for Schrödinger operators with a positive double well potential as well as an upper bound for the derivatives of the eigenfunctions (see [3]) one shows that the integral  $A(u)$  is convergent and moreover

$$P_1(x, D)A(u) = 0.$$

Before concluding the proof of the sharpness of the Gevrey  $s_0$  regularity for  $A(u)$ , we need to make sure that the function  $u = u_1 u_2$  does not have any effect on the convergence of the integral at infinity as well as on the Gevrey behavior of  $A(u)$ .

As far as  $u_1$  is concerned, this is fairly obvious, since  $u_1$  is a rapidly decreasing function of  $\tau(\rho)\rho^{\frac{1}{r}}x_1$ , where  $\tau(\rho)$  is defined before equation (4.5), and, computing this function at the origin—as we need to do—will not affect the exponential in  $A(u)$ . We are thus left with  $u_2 = u_2(\rho^{\frac{1}{q}}x_2, \rho)$ . Even though  $u_2$  is rapidly decreasing w.r.t.  $\rho^{\frac{1}{q}}x_2$ , we still need some estimate on  $u_2$  allowing us to conclude that  $u_2$  can be polynomially bounded in  $\rho$ , uniformly for  $x_2$  in a neighborhood of the origin and moreover that  $u_2(0, \rho)$  does not vanish for large  $\rho$  with so high a speed to compromise the Gevrey  $s_0$  regularity.

To this end we need an estimate of  $u$  in a classically forbidden region, i.e. when  $\hbar = \frac{h}{z_2(h)^{\frac{q}{q-p}}}$  is small ( $\rho$  is large) and  $x$  is in a neighborhood of the origin. This can be done by resorting to the following theorem providing a lower bound for the tunneling of the solution:

**Theorem 4.3** (See [61], Theorem 7.7). *Let  $U$  be a neighborhood of the origin in  $\mathbb{R}$ . There exist positive constants  $C, \hbar_0$  such that*

$$(4.14) \quad \|u\|_{L^2(U)} \geq e^{-\frac{C}{\hbar}} \|u\|_{L^2(\mathbb{R})},$$

for  $0 < \hbar \leq \hbar_0$ .

To finish the proof we argue for an even eigenfunction. A similar argument can be done for the odd eigenfunctions.

We may assume that

$$\|u\|_{L^2(\mathbb{R})} = 1, \quad u(0, \hbar) > 0,$$

since  $u'(0, \hbar) = 0$  because of its parity and if  $u(0, \hbar) = 0$  would imply that  $u$ , being a solution of a homogeneous differential equation, is identically zero.

Moreover, since  $u$  solves

$$(4.15) \quad Q_{\hbar}(x, \partial_x)u = E(\hbar)u,$$

we have  $\partial_x^2 u(0, \hbar) > 0$ .

Denote by  $x_0 = x_0(\hbar)$  the first positive zero of  $V(x) - E(\hbar) = x^{2(q-1)} - x^{2(p-1)} - \hat{\gamma} - E(\hbar)$ . Note that  $u$  is strictly positive in the interval  $0 \leq x \leq x_0$ . In fact, by contradiction, denoting by  $\bar{x}$  the first zero of  $u$  in  $[0, x_0]$ , by (4.15), we may conclude that  $u'' > 0$  in  $[0, \bar{x}[$  so that the same is true for  $u'$ . Hence  $u(\bar{x}, \hbar) > u(0, \hbar) > 0$ , which is absurd.

By (4.15),  $u$  is strictly convex for  $0 \leq x \leq x_0$  and has its minimum at the origin and its maximum at  $x_0$ .

Define  $y = \frac{\partial_x u}{u}$ . We have  $y > 0$  if  $0 < x \leq x_0$ . Then, writing  $y'$  for  $\partial_x y$ ,

$$y' = \frac{V - E}{\hbar^2} - y^2.$$

The function  $y$  has a maximum in the interval  $]0, x_0[$ . In fact  $y'(0) > 0$  and  $y'(x_0) = -y^2(x_0) < 0$ . Denote by  $\bar{x}$  the point where the maximum is attained: it lies in the interior of the interval  $[0, x_0]$ . Moreover we get

$$y(\bar{x}) = \frac{(V(\bar{x}) - E(\hbar))^{1/2}}{\hbar}.$$

From the definition of  $y$  we obtain

$$\begin{aligned} u(0) &= e^{-\int_0^{x_0} y(s) ds} u(x_0) \geq e^{-x_0 y(\bar{x})} \frac{1}{\sqrt{2x_0}} \|u\|_{L^2([-x_0, x_0])} \\ &\geq \frac{1}{\sqrt{2x_0}} e^{-\frac{(-\tilde{\gamma})^{1/2}}{\hbar}} e^{-\frac{c}{\hbar}}. \end{aligned}$$

Here we used Theorem 4.3,  $x_0 < 1$ ,  $E(\hbar) > 0$  and  $u$  is normalized. We remark that  $x_0(\hbar) \rightarrow \hat{x}_0 > 0$  when  $\hbar \rightarrow 0+$ .

We are now in a position to conclude the proof of Theorem 4.2 for an even function  $u_2$ . We recall that

$$\hbar = \mathcal{O}\left(\rho^{\left(\frac{1}{q} - \frac{1}{r}\right)\frac{q}{q-1}}\right) = \mathcal{O}(\rho^{-\varkappa}).$$

Compute

$$\begin{aligned} (-D_{x_4})^k \partial_{x_1}^\varepsilon A(u)(0) &= \int_{M_u}^{+\infty} e^{-\rho^\theta} \rho^{k+\frac{\varepsilon}{r}} \tau(\rho)^\varepsilon \partial^\varepsilon u_1(0) u_2(0, \rho) d\rho \\ &\geq \partial^\varepsilon u_1(0) C \int_{M_u}^{+\infty} e^{-\rho^\theta - C_1 \rho^\varkappa} \tau(\rho)^\varepsilon \rho^{k+\frac{\varepsilon}{r}} d\rho \geq C_2^{k+1} k!^{s_0}, \end{aligned}$$

where  $\varepsilon = 0$  or  $1$  if  $u_1$  is even or odd respectively and

$$\varkappa = \left(\frac{1}{r} - \frac{1}{q}\right) \frac{q}{q-1} < \theta.$$

The last inequality above holds since

$$\begin{aligned} \int_{M_u}^{+\infty} e^{-\rho^\theta - C_1 \rho^\varkappa} \tau(\rho)^\varepsilon \rho^{k+\frac{\varepsilon}{r}} d\rho &\geq C_\tau \int_{M_u}^{+\infty} e^{-c\rho^\theta} \rho^k d\rho \\ &= -C_\tau \int_0^{M_u} e^{-c\rho^\theta} \rho^k d\rho + C_2^{k+1} k!^{s_0} \\ &\geq C_2^{k+1} k!^{s_0} \left(1 - C_\tau C_2^{-(k+1)} M_u e^{-cM_u^\theta} \frac{M_u^k}{k!^{s_0}}\right) \geq C_3^{k+1} k!^{s_0}, \end{aligned}$$

if  $k$  is suitably large and  $C_3$  is suitable.

We emphasize that in a global (or semiglobal) setting the operator  $P_1$  may be analytic hypoelliptic, suggesting that analytic hypoellipticity might be a consequence of the spectral behavior of some operator. Concerning this we cite the following theorem by Chinni [17]:

**Theorem 4.4** ([17]). *Let*

$$P_1(x, D) = D_1^2 + D_2^2 + a^2(x_1) (D_3^2 + D_4^2) + b_1^2(x_2) D_3^2 + b_2^2(x_2) D_4^2,$$

defined on  $\mathbb{T}^4$ , where  $a, b_1, b_2$  are real valued real analytic functions not identically zero. Then, given any subinterval  $I \subset \mathbb{T}_{x'}^2$ ,  $x' = (x_1, x_2)$ , and given any  $u \in \mathcal{D}'(I \times \mathbb{T}_{x''}^2)$ ,  $x'' = (x_3, x_4)$ , the condition  $P_1 u \in C^\omega(I \times \mathbb{T}_{x''}^2)$  implies  $u \in C^\omega(I \times \mathbb{T}_{x''}^2)$ .

We note that the same phenomenon of Theorem 4.2 occurs when the Treves conjecture gives a more complicated stratification. Consider for example the following operator

$$(4.16) \quad P(x, D) = D_1^2 + x_1^{2(\ell+r-1)} (D_3^2 + D_4^2) + x_1^{2\ell} \left[ D_2^2 + x_2^{2(p-1)} D_3^2 + x_2^{2(q-1)} D_4^2 \right],$$

where  $\ell, r, p, q \in \mathbb{N}$ ,  $1 < r < p < q$ , and  $x = (x_1, \dots, x_4) \in \mathbb{R}^4$ .

Hörmander's condition is satisfied by  $P$  and thus  $P$  is  $C^\infty$  hypoelliptic.

The characteristic manifold of  $P$  is the real analytic manifold

$$(4.17) \quad \text{Char}(P) = \left\{ (x, \xi) \in T^*\mathbb{R}^4 \setminus \{0\} \mid \xi_1 = 0, x_1 = 0, \xi_2^2 + \xi_3^2 + \xi_4^2 > 0 \right\}.$$

According to Treves conjecture one has to look at the strata associated with  $P$ .

The stratification associated with  $P$  is made up of two symplectic strata:

a -

$$\Sigma_1 = \left\{ (0, x_2, x_3, x_4; 0, \xi_2, \xi_3, \xi_4) \mid \xi_2^2 + x_2^2 > 0, \sum_{j=2}^4 \xi_j^2 > 0 \right\}.$$

This is a symplectic stratum and the restriction of the symplectic form to it has rank 6.

b -

$$\Sigma_2 = \left\{ (0, 0, x_3, x_4; 0, 0, \xi_3, \xi_4) \mid \xi_3^2 + \xi_4^2 > 0 \right\}.$$

This is also a symplectic stratum and the restriction of the symplectic form to it has rank 4.

According to the conjecture we would expect local real analyticity near the origin for the distribution solutions,  $u$ , of  $Pu = f$ , with a real analytic right hand side.

The following theorem holds

**Theorem 4.5** ([10]). *Let*

$$\frac{1}{s_\ell} = \frac{\ell + 1}{\ell + r} + \frac{r - 1}{\ell + r} \frac{p - 1}{q - 1}.$$

Then  $P$  is locally Gevrey  $s_\ell$  hypoelliptic and not better near the origin.

Note that for  $\ell = 0$   $s_\ell$  coincides with  $s_0$  of Theorem 4.2.

We also would like to mention the following result: let  $r, p, q$  and  $k$  be positive integers such that  $r < p < q$ . Consider the sum of squares operator in  $\mathbb{R}^4$ , obtained adding the square of the vector field  $x_2^{p-1}x_3^kD_4$  to the operator in (4.3),

$$(4.18) \quad \begin{aligned} P(x, D) = & D_1^2 + D_2^2 + x_1^{2(r-1)}D_3^2 + x_1^{2(r-1)}D_4^2 + x_2^{2(p-1)}D_3^2 \\ & + x_2^{2(p-1)}x_3^{2k}D_4^2 + x_2^{2(q-1)}D_4^2 \end{aligned}$$

The characteristic variety of  $P$  is actually the real analytic manifold

$$\text{Char}(P) = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3^2 + \xi_4^2 > 0\},$$

which is a symplectic manifold. Actually  $\text{Char}(P) = \text{Char}(P_1)$ .

We have

**Theorem 4.6** ([11]). *The operator  $P$  in (4.18) is analytic hypoelliptic.*

The theorem above as well as the choice of the operator  $P$  are worth some explanation.

The operator  $P_1$  in (4.3) is a counterexample to Treves conjecture. Actually the stratification associated to  $P_1$  in the statement of the conjecture is made of the sole stratum

$$\text{Char}(P_1) = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3^2 + \xi_4^2 > 0\} = \text{Char}(P).$$

An inspection of the proof though, shows that the real analytic submanifold

$$\Sigma_1 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 = 0, \xi_4 \neq 0\}$$

is important for the Gevrey regularity of  $P_1$  because of the presence of the vector field  $x_2^{p-1}D_3$ . This remark would lead us to consider the characteristic set  $\text{Char}(P_1)$  as the disjoint union of the following two analytic strata

$$\Sigma_0 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 \neq 0\},$$

$$\Sigma_1 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 = 0, \xi_4 \neq 0\}.$$

Actually  $\Sigma_1$  is non symplectic and has Hamilton leaves which are the  $x_3$  lines where the propagation of the Gevrey- $s_0$  wave front set occurs. Hence we might think of  $\Sigma_1$  as a ‘‘non Treves stratum’’ where the existence of Hamilton leaves implies non analytic regularity.

We must make it clear though that, to our knowledge, there is neither a replacement conjecture nor an alternative definition of stratification.

The model operator  $P$  is such that, even though almost all the properties of  $P_1$ , as far as the Treves stratification is concerned, are retained, the manifold  $\Sigma_1$  is replaced by

$$(4.19) \quad \Sigma_1 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, 3, \xi_4 \neq 0\},$$

due to the presence in  $P$  of both vector fields  $x_2^{p-1}D_3$  and  $x_2^{p-1}x_3^kD_3$ . We point out that in this case  $\Sigma_1$  is a symplectic submanifold and hence has no Hamilton leaves.

In other words it seems that the analytic regularity of a sum of squares should depend on a suitable stratification of the characteristic variety of the operator and on the fact that its strata are analytic symplectic manifolds.

Unfortunately we cannot be more precise on this at the moment.

## 5. OPEN PROBLEMS

**5.1. The 2 dimensional case.** Let us consider a sum of squares operator in  $\mathbb{R}^2$ . Denote by  $(x, y)$  the variables in  $\mathbb{R}^2$ :

$$(5.1) \quad P(x, y, D_x, D_y) = \sum_{j=1}^N X_j^2(x, y, D_x, D_y).$$

Without loss of generality we may suppose we are working in a neighborhood of the origin,  $\Omega$ , and that  $X_1 = D_x$ .

Thus one of the equations of the characteristic variety is  $\xi = 0$ . For  $j \geq 2$  we may then write  $X_j(x, y, \xi, \eta) = a_j(x, y)\xi + b_j(x, y)\eta$ . Since  $\eta \neq 0$  we find that the other relations describing the characteristic variety are  $b_j(x, y) = 0$ , where the  $b_j$  are real analytic functions defined in  $\Omega$ .

Since we are assuming that Hörmander condition is satisfied, we may suppose that  $(0, 0)$  is a point of the characteristic variety and that, possibly shrinking  $\Omega$ , there is an index  $j$ ,  $2 \leq j \leq N$ , such that  $\partial_x^m b_j(0, 0) \neq 0$ ; here  $m$  is minimal, i.e.  $\partial_x^k b_j(0, 0) = 0$  when  $2 \leq j \leq N$  and  $k < m$ . It is also evident that  $X_1 = D_x$  is the only field that we can meaningfully use to form brackets of vector fields, i.e. we have to consider only brackets of the form  $\text{ad}(X_1)^k X_j$ , since any other vector field has a vanishing coefficient in front (see also [14].)

Set

$$f(x, y) = \sum_{j=2}^N (b_j(x, y))^2.$$

The characteristic variety of  $P$  is then given by

$$\text{Char}(P) = \{(x, y; 0, \eta) \mid \eta \neq 0, f(x, y) = 0\}.$$

We apply Weierstraß preparation theorem to  $f$  and write

$$f(x, y) = e(x, y) \left( x^{2m} + \sum_{\ell=1}^{2m} a_\ell(y) x^{2m-\ell} \right),$$

where  $e(0, 0) \neq 0$  is a  $C^\omega$  function,  $a_\ell(0) = 0$  for every  $\ell = 1, \dots, 2m$ . Since  $e$  is different from zero, we may replace  $f$  by the Weierstraß polynomial above, because they define the same variety. Let us denote it by  $q(x, y)$ .

**Definition 5.1** ([41], [60]). *We say that a polynomial of the form*

$$q(z', z_n) = z_n^m + \sum_{k=1}^m a_k(z') z_n^{m-k},$$

*is a Weierstraß type polynomial of degree  $m$  if  $z = (z', z_n) \in U$  open subset of  $\mathbb{C}^n$ ,  $0 \in U$ ,  $a_k \in \mathcal{O}(U)$ , holomorphic functions on  $U$  such that  $a_k(0) = 0$  for every  $k$  is a Weierstraß type polynomial of degree  $m$ .*

We have the following theorem

**Theorem 5.1** ([41], [60]). *Let  $f$  be a holomorphic function defined in a neighborhood of the origin,  $U \subset \mathbb{C}^n$ . Suppose that  $f(0, \dots, 0, z_n) \not\equiv 0$  in  $U$ . Then there exists a Weierstraß type polynomial,  $q^\#$ , whose discriminant is not identically zero in  $U$  and such that  $f = 0$  iff  $q^\# = 0$ .*

*Same statement for a real analytic case.*

Denote by  $D_\#(y) = \text{discr } q^\#$ . We have that  $D_\# \in C^\omega(\pi_2(U))$ , where  $\pi_2$  is the projection onto the  $y$ -axis.

As a consequence  $D_\#^{-1}(0) = \{y_1, \dots, y_\nu\}$ , for a certain  $\nu \in \mathbb{N}$ . Let  $m^\# = \deg q^\#$  and denote by  $\rho_1, \dots, \rho_{m^\#}$  the roots (real or complex) of  $q^\#$ . For every  $j \in \{1, \dots, \nu\}$ , there are at least two indices,  $i_1, i_2$  in the range  $\{1, \dots, m^\#\}$  such that  $\rho_{i_1}(y_j) = \rho_{i_2}(y_j)$ . We set

$$(5.2) \quad \tilde{\rho}_j = (x_{i_1}, y_j), \quad x_{i_1} = \rho_{i_1}(y_j), \quad j = 1, \dots, \nu.$$

**Definition 5.2.** *We call  $\tilde{\rho}_j$  a branching point of  $f^{-1}(0)$ . Denote by  $\mathcal{B}(U)$  the set of branching points in  $U$ .*

The above described facts determine the stratification. There are two cases:

- (a) The set  $\mathcal{B}(U)$  is empty. This means that the roots of  $q^\#$  are simple and have the form  $x = \rho_k(y)$ ,  $k = 1, \dots, m^\#$ . Since, according to our assumption,  $(0, 0) \in f^{-1}(0)$ , we deduce that there is only one  $k \in \{1, \dots, m^\#\}$  such that  $\rho_k(0) = 0$ . Possibly shrinking  $U$  we obtain that  $f$  has the form

$$f(x, y) = \tilde{e}(x, y)(x - \rho(y))^{2m'}, \quad \tilde{e}(0, 0) \neq 0, \quad m' \leq m.$$

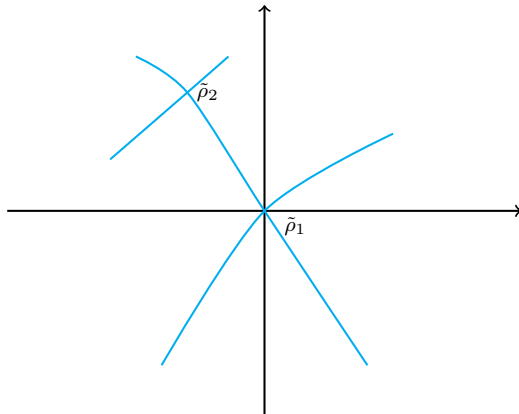


FIGURE 1. An example of  $f^{-1}(0)$  near  $(0, 0) = \tilde{\rho}_1$

The characteristic variety of  $P$  is then symplectic and  $P$  is analytic hypoelliptic. This has been proved by Ōkaji, [48], and Cordaro and Hanges, [21], for operators where  $f$  has the above form.

- (b) The set  $\mathcal{B}(U)$  is not empty. Then we may always shrink the neighborhood  $U$  so that the origin—or  $\tilde{\rho}_1$  is the only branching point in  $U$ . Then  $f$  has the form

$$f(x, y) = \tilde{e}(x, y) \prod_{j=1}^{m'} (x - \rho_j(y))^{m_j},$$

and  $\rho_j(y) \neq \rho_k(y)$  if  $y \neq 0$ , but  $\rho_j(0) = 0$  for every  $j$ ,  $m' \leq m^\#$ ,  $\tilde{e}(0, 0) \neq 0$ .

The deeper stratum is

$$\Sigma_1 = \{(0, 0; 0, \eta) \mid \eta \neq 0\},$$

as we can see by taking derivatives of  $f$  with respect to  $x$ .  $\text{Char}(P) \setminus \Sigma_1$  is a union of disjoint arcs of  $C^\omega$  curves of the form

$$\{(x, y, 0, \eta) \mid \eta \neq 0, (x, y) \neq (0, 0), x = \rho_j(y)\},$$

which gives symplectic strata at each point of which we get real analyticity.

Thus it seems that the Treves stratification completely describes all possible situations in two dimensions. The problem of the non analytic hypoellipticity of  $P$  in case (b) as well as the problem of its (optimal) Gevrey regularity are open (see [14] for a particular case.)

We explicitly note that proving that in case (b) there is no analytic hypoellipticity amounts to proving that the Treves conjecture holds in dimension two.

**5.2. The 3 dimensional case.** There are no known counterexamples to the Treves conjecture in dimension 3. However in [12] some examples have been proposed that should violate the conjecture. We briefly describe those models in this section.

Let  $x \in \mathbb{R}^2$ ,  $y \in \mathbb{R}$ ,  $a, p, q, r$  be positive integers. We shall specify later the relation between these integers. Define

$$(5.3) \quad Q(x, y, D_x, D_y) = D_1^2 + D_2^2 + x_2^{2(r-1)} D_y^2 + x_1^{2(q-1)} D_y^2 + x_1^{2(p-1)} y^{2a} D_y^2.$$

If we assume that  $1 < p < q < r$ , the Lie algebra is generated with brackets of length  $m = q - 1$ . The characteristic manifold is  $\{(0, 0, y; 0, 0, \eta) \mid \eta \neq 0\}$ .

Looking at the powers of the monomials in  $x$ , we can draw a (convex) Newton polygon in the  $x$ -plane; the precise definition of Newton polygon is given in [12], but, in three variables, it is just a segment—the red line in the figures below. When the powers of  $x$  having a possibly degenerate coefficient are added to the picture we obtain

where the dashed line has slope  $-1$  and starts from the vertex closest to the origin, the triangle underneath the dashed line has points corresponding to monomials where the Treves stratification identifies a non symplectic stratum.

In [12] it is proved that

**Theorem 5.2.** *The operator  $Q$  in (5.3) is Gevrey  $s$  hypoelliptic for*

$$s \geq \left(1 - \frac{1}{a} \frac{p-1}{q}\right)^{-1}.$$

There is no proof of the optimality of the above index; we believe that it is optimal, due to the fact that Theorem 5.2 is a particular case of a result proved in [12], which, in the known cases, gives optimal values.

Let us now consider the operator  $Q$  in (5.3) when  $1 < r < p < q$ . If, as we did before, we draw the Newton polygon for  $Q$  and add to the picture the dots corresponding to degenerate monomials (i.e. monomials having coefficients containing powers of  $y$ ) we obtain

In [12] it is proved that, in the latter case,  $Q$  is Gevrey  $s$  hypoelliptic for

$$(5.4) \quad s \geq \left(1 - \frac{1}{a} \cdot \frac{q-p}{q-1} \cdot \frac{r-1}{r}\right)^{-1}.$$

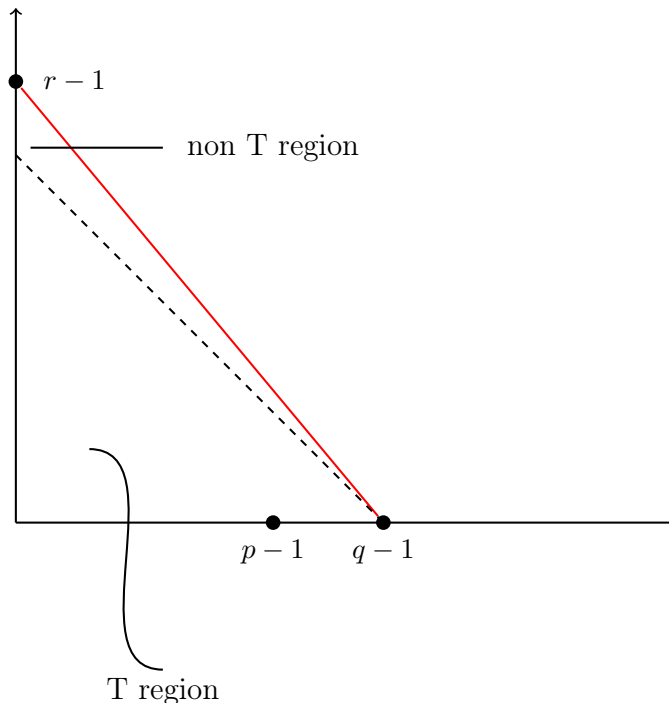


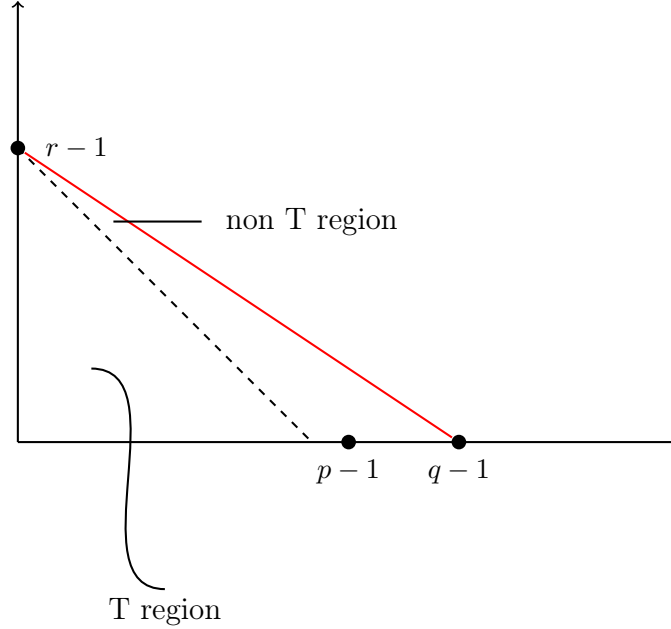
FIGURE 2. The Newton polygon for  $Q$  in (5.3) when  $1 < p < q < r$

On the other hand  $Q$  has a symplectic characteristic manifold:  $\text{Char}(Q) = \{x = \xi = 0, \eta \neq 0\}$  and no strata are found using the Poisson brackets of the fields, so that according to the conjecture it should be analytic hypoelliptic. We believe that the Gevrey regularity in (5.4) is optimal, based on the striking similarity of  $Q$  with the operator discussed in [3] which violates the conjecture. Actually the main difference between  $Q$  and the operator in [3] consists in the fact that the putative stratum is a non symplectic “stratum” whose Hamilton leaf lies on the fiber of the cotangent bundle.

At the moment we have no optimality proof for the Gevrey regularity (5.4) of  $Q$  both in the case of Figure 2 and of Figure 3. We also remark that the optimality of (5.4) would imply that the Treves conjecture does not hold in dimension 3.

Even though for the case considered in [12] the Newton polygon helps in identifying a (non symplectic) stratum in the three variables case, we would like to point out that this is not the case when the vector fields are not monomials. Here are two examples:

$$(5.5) \quad Q_1 = D_1^2 + D_2^2 + (x_1 - x_2)^2 D_y^2 + (y^2 x_1^3 + x_2^4)^2 D_y^2$$

FIGURE 3. The Newton polygon for  $Q$  when  $1 < r < p < q$ 

and

$$(5.6) \quad Q_2 = D_1^2 + D_2^2 + (x_1 - x_2)^2 D_y^2 + (x_1^3 + y^2 x_2^4)^2 D_y^2.$$

It is easy to show that

$$\text{Char}(Q_j) = \{(0, 0, y; 0, 0, \eta) \mid \eta \neq 0\},$$

i.e. a symplectic manifold.

One can prove, using the  $L^2$  estimate, that  $Q_1$  is analytic hypoelliptic. Unfortunately the same proof does not work for  $Q_2$ . We believe that  $Q_2$  has a non symplectic non Treves stratum, and hence is not analytic hypoelliptic. No proof is known.

A similar model is

$$(5.7) \quad Q_3 = D_1^2 + D_2^2 + (yx_1^\ell + x_2^m)^2 D_y^2 + x_1^{2k} D_y^2.$$

We can show that

$$Q_3 \text{ is analytic hypoelliptic if } \begin{cases} m = 1, \\ \ell \geq k. \end{cases}$$

On the other hand we believe that  $Q_3$  is not analytic hypoelliptic when  $m > 1$  and  $\ell < k$  even though there is no proof of this fact. Note that, depending on the relations between  $m$  and  $k$  we may or may not have a Treves non symplectic stratum.

**5.3. The case of dimension  $n \geq 3$ .** Finally let us consider the “general” case, i.e. the case of dimension  $n$ . Even though we have seen a number of examples where the Treves stratification does not identify a non symplectic stratum, while the operator is not analytic hypoelliptic, like those of Theorem 4.2 and 4.5, we think that the important idea in the formulation of the conjecture is the quest for a stratification.

Actually the stratification associated to  $P_1$  in (4.3), is made of the sole stratum

$$\text{Char}(P_1) = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3^2 + \xi_4^2 > 0\}.$$

An inspection of the proof though, shows that the real analytic submanifold

$$\Sigma_1 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 = 0, \xi_4 \neq 0\}$$

is important for the Gevrey regularity of  $P_1$  because of the presence of the vector field  $X_5 = x_2^{p-1}D_3$ . This remark would lead us to consider the characteristic set  $\text{Char}(P_1)$  as the disjoint union of the following two analytic strata

$$\Sigma_0 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 \neq 0\},$$

$$\Sigma_1 = \{(x, \xi) \mid x_i = \xi_i = 0, i = 1, 2, \xi_3 = 0, \xi_4 \neq 0\}.$$

$\Sigma_1$  is non symplectic and has Hamilton leaves which are the  $x_3$  lines where the propagation of the Gevrey- $s_0$  wave front set occurs. Hence we might think of  $\Sigma_1$  as a “non Treves stratum” where the existence of Hamilton leaves implies non analytic regularity.

Somewhat symmetrically the analog of  $\Sigma_1$  for the operator  $P$  of (4.18) turns out to be symplectic.

The following question has, to our knowledge, received no answer yet:

**Problem 5.1.** *Define a stratification of the characteristic variety in real analytic manifolds such that when each stratum is a symplectic manifold then the operator is analytic hypoelliptic.*

This would allow to reformulate, regardless of the local or microlocal aspect of the question, Treves conjecture as

**Conjecture 5.2.** *A sum of squares operator with real analytic coefficients is analytic hypoelliptic if and only if every stratum of the stratification is a symplectic real analytic manifold.*

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