

# Normal operators of double fibration transforms

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## **$d$ -plane transform on $\mathbb{R}^n$**

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## $d$ -plane transform on $\mathbb{R}^n$

- Let  $n = 2, 3, 4, \dots$ , and let  $d = 1, \dots, n - 1$ .
- Grassmannian  $G_{d,n} :=$  the set of all  $d$ -dimensional vector subspaces of  $\mathbb{R}^n$ .
- For any  $\sigma \in G_{d,n}$ , we have an orthogonal decomposition  $x = x' + x'' \in \sigma \oplus \sigma^\perp = \mathbb{R}^n$ .
- Affine Grassmannian  $G(d, n) :=$  the set of all  $d$ -dimensional planes in  $\mathbb{R}^n$ , i.e.,

$$G(d, n) := \{(\sigma, x'') : \sigma \in G_{d,n}, x'' \in \sigma^\perp\}.$$

- The  $d$ -plane transform of  $f \in \mathcal{S}(\mathbb{R}^n)$  is defined by

$$R_d f(\sigma, x'') := \int_{\sigma} f(x' + x'') dx', \quad (\sigma, x'') \in G(d, n),$$

where  $dx'$  is the Lebesgue measure on  $\sigma$ .

- $R_1$  and  $R_{n-1}$  are said to be the X-ray transform and the Radon transform on  $\mathbb{R}^n$  respectively, and  $R_1 = R_{n-1}$  when  $n = 2$ .

## The normal operator of the $d$ -plane transform

- The formal adjoint of  $R_d$  of a continuous function  $\varphi$  on  $G(d, n)$  is explicitly given by

$$R_d^* \varphi(x) := \frac{1}{C(d, n)} \int_{O(n)} \varphi(x + k \cdot \sigma) dk,$$

where  $C(d, n) = (4\pi)^d \Gamma(n/2)/\Gamma((n-1)/2)$ ,  $\Gamma(\cdot)$  is the gamma function,  $O(n)$  is the orthogonal group,  $dk$  is the normalized measure which is invariant under rotations, and  $\sigma \in G_{d,n}$  is arbitrary.  $R_d$  and  $R_d^*$  are elliptic Fourier integral operators.

- The normal operator is  $R_d^* R_d = (-\Delta_{\mathbb{R}^n})^{-d/2}$ , and the excess  $e$  for  $R_d^* R_d$ , which is the degeneracy of the phase function of  $R_d^* R_d$ , is

$$e = \dim(G(d, n)) - \dim(\mathbb{R}^n) = (d+1)(n-d) - n = d(n-d-1).$$

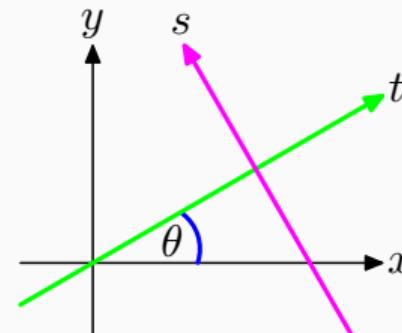
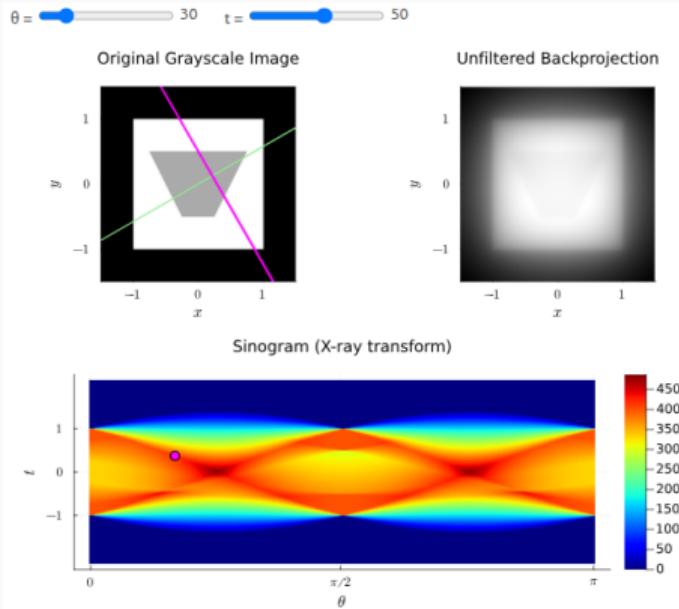
This gives the inversion formula  $f = (-\Delta_{\mathbb{R}^n})^{d/2} R_d^* R_d f$  for  $f(x) = \mathcal{O}(\langle x \rangle^{-d-\varepsilon})$ .

- We can consider the **invertibility** for more general operators arising in integral geometry via the normal operators.

## X-ray transform on $\mathbb{R}^2$

Let  $n = 2$ . The X-ray transform of a function  $f$  of  $(x, y) \in \mathbb{R}^2$  is defined by

$$R_1 f(\theta, \textcolor{red}{t}) := \int_{-\infty}^{\infty} f(\textcolor{red}{t} \cos \theta - \textcolor{blue}{s} \sin \theta, \textcolor{red}{t} \sin \theta + \textcolor{blue}{s} \cos \theta) d\textcolor{blue}{s}, \quad (\theta, t) \in [0, \pi] \times \mathbb{R}.$$



## Conormal distributions

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## Conormal distributions

### Definition 1 (Conormal distributions)

Let  $X$  be an  $N$ -dim manifold, and let  $Y$  be a closed submanifold of  $X$ .  $u \in \mathcal{D}'(X)$  is said to be conormal with respect to  $Y$  of degree  $m$  if

$$L_1 \cdots L_M u \in {}^\infty H_{(-m-N/4)}^{\text{loc}}(X)$$

for all  $M = 0, 1, 2, \dots$  and all vector fields  $L_1, \dots, L_M$  tangential to  $Y$ . Denote by  $I^m(X, N^* Y)$ , the set of all distributions on  $X$  conormal with respect to  $Y$  of degree  $m$ .

Note that  $N_y^* Y := T_y^* X / T_y^* Y$  for any  $y \in Y$ . If  $u \in I^m(X, N^* Y)$ , then  $\text{WF}(u) \subset N^* Y \setminus 0$ .

$$\|u\|_{{}^\infty H_{(s)}(\mathbb{R}^N)} := \sup_{j=0,1,2,\dots} \left( \int_{A_j} \langle \xi \rangle^{2s} |\hat{u}(\xi)|^2 d\xi \right)^{1/2},$$

$$A_0 := \{|\xi| < 1\}, \quad A_j := \{2^{j-1} \leq |\xi| < 2^j\}, j = 1, 2, 3, \dots.$$

## Conormal distributions and oscillatory integrals

### Proposition 2 (Characterization of conormal distributions)

Let  $x = (x', x'') \in \mathbb{R}^k \times \mathbb{R}^{N-k}$  and let  $Y = \mathbb{R}^k \times \{0\} = \{x'' = 0\}$ . Then  $u \in \mathcal{D}'(\mathbb{R}^N)$  belongs to  $I^{m+k/2-N/4}(\mathbb{R}^n, N^* Y)$  if and only if there exists an amplitude  $a(x'', \xi') \in S^m(\mathbb{R}^{N-k} \times \mathbb{R}^k)$  such that

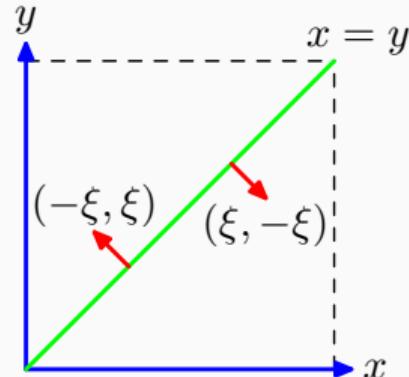
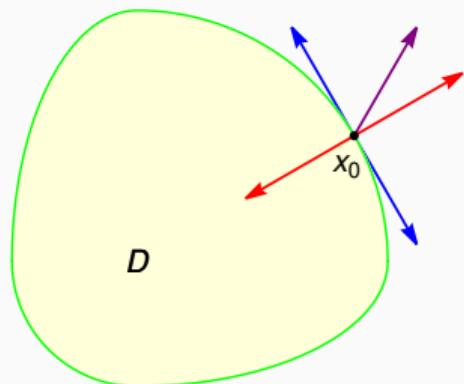
$$u(x) = \int_{\mathbb{R}^k} e^{ix' \cdot \xi'} a(x'', \xi') d\xi'.$$

We can replace the conormal bundle  $N^* Y$  by more general Lagrangian distributions  $\Lambda$ . The elements of  $I^m(X, \Lambda)$  are said to be Lagrangian distributions on  $X$ . These are characterized as oscillatory integrals with more general phase functions. The distributions kernels of Fourier integral operators are Lagrangian distributions. Rigorously we should use the set of distribution sections of the half-density bundle  $I^m(X, \Lambda; \Omega_X^{1/2})$ .

## Examples of conormal distributions

- $\chi_D \in I^{-1/2-n/4}(N^*\partial D)$ , where  $D$  is a domain in  $\mathbb{R}^n$  with smooth boundary.
- Set  $\Delta = \{(x, x) : x \in \mathbb{R}^N\}$ . If  $a(x, \xi) \in S^m(\mathbb{R}^N \times \mathbb{R}^N)$ , then

$$K(x, y) = \int_{\mathbb{R}^N} e^{i(x-y)\cdot\xi} a(x, \xi) d\xi \in I^m(\mathbb{R}^N \times \mathbb{R}^N, N^*\Delta).$$



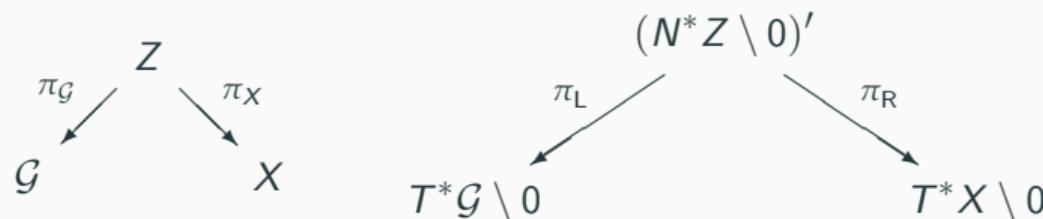
## Double fibration transforms

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## Double fibration

Following Mazzucchelli-Salo-Tzou [3], we introduce double fibration transforms.

- Let  $\mathcal{G}$  and  $X$  be oriented smooth manifolds without boundaries.  $N := \dim(\mathcal{G})$  and  $n := \dim(X)$ . Denote by  $d\mathcal{G}$  and  $dX$  the orientation forms of  $\mathcal{G}$  and  $X$  respectively.
- Let  $Z$  be an oriented embedded submanifold of  $\mathcal{G} \times X$ , and let  $dZ$  be the orientation form.
- Assume that  $N + n > \dim(Z) > N \geq n \geq 2$ , and set  $n' := \dim(Z) - N$  and  $n'' := n - n'$ . Then  $\dim(Z) = N + n'$ ,  $n = n' + n''$  and  $n', n'' = 1, \dots, n - 1$ .



- We assume that  $Z$  is a **double fibration**, that is, the natural projections  $\pi_{\mathcal{G}} : Z \rightarrow \mathcal{G}$  and  $\pi_X : Z \rightarrow X$  are submersions respectively.

## Orientation forms on $G_z := \pi_x \circ \pi_{\mathcal{G}}^{-1}(z)$ and $H_x := \pi_{\mathcal{G}} \circ \pi_X^{-1}(x)$

- $G_z := \pi_x \circ \pi_{\mathcal{G}}^{-1}(z)$  becomes an  $n'$ -dim submanifold of  $X$  for any  $z \in \mathcal{G}$ , and  $H_x := \pi_{\mathcal{G}} \circ \pi_X^{-1}(x)$  forms an  $(N - n'')$ -dim submanifold of  $\mathcal{G}$  for any  $x \in X$ .
- Fix arbitrary  $(z, x) \in Z$ , and let  $\{v_1, \dots, v_n\}$  and  $\{w_1, \dots, w_N\}$  be bases of  $T_x X$  and  $T_z \mathcal{G}$  respectively such that

$$T_{(z,x)}Z = \text{span}\langle v_1, \dots, v_{n'}, w_1, \dots, w_N \rangle = \text{span}\langle v_1, \dots, v_n, w_1, \dots, w_{N-n''} \rangle.$$

The induced orientation forms  $dG_z$  on  $G_z$  and  $dH_x$  on  $H_x$  are given by

$$\begin{aligned} dG_z(d\pi_X(v_1), \dots, d\pi_X(v_{n'})) &:= dZ_{\pi_{\mathcal{G}}^{-1}(z)}(v_1, \dots, v_{n'}) \\ &= \frac{dZ(v_1, \dots, v_{n'}, w_1, \dots, w_N)}{d\mathcal{G}(d\pi_{\mathcal{G}}(w_1), \dots, d\pi_{\mathcal{G}}(w_N))}, \end{aligned}$$

$$\begin{aligned} dH_x(d\pi_{\mathcal{G}}(w_1), \dots, d\pi_{\mathcal{G}}(w_{N-n''})) &:= dZ_{\pi_X^{-1}(x)}(w_1, \dots, w_{N-n''}) \\ &= \frac{dZ(v_1, \dots, v_n, w_1, \dots, w_{N-n''})}{dX(d\pi_X(v_1), \dots, d\pi_X(v_n))}. \end{aligned}$$

## Double fibration transform

Suppose that a weight function  $\kappa(z, x) \in C^\infty(\mathcal{G} \times X)$  is nowhere vanishing. A double fibration transform  $\mathcal{R}$  associated with the double fibration  $Z$  is defined by

$$\mathcal{R}f(z) := \left( \int_{G_z} \kappa(z, x) \frac{f}{|dX|^{1/2}}(x) dG_z(x) \right) |d\mathcal{G}(z)|^{1/2}$$

for  $f \in \mathcal{D}(X, \Omega_X^{1/2})$ . The adjoint  $\mathcal{R}^*$  is given by

$$\mathcal{R}^* u(x) = \left( \int_{H_x} \overline{\kappa(z, x)} \frac{u}{|d\mathcal{G}|^{1/2}}(z) dH_x(z) \right) |dX(x)|^{1/2}$$

for  $u \in \mathcal{D}(\mathcal{G}, \Omega_{\mathcal{G}}^{1/2})$ . Then we deduce that

$$\mathcal{R} : \mathcal{D}(X, \Omega_X^{1/2}) \rightarrow \mathcal{E}(\mathcal{G}, \Omega_{\mathcal{G}}^{1/2}), \quad \mathcal{R}^* : \mathcal{D}(\mathcal{G}, \Omega_{\mathcal{G}}^{1/2}) \rightarrow \mathcal{E}(X, \Omega_X^{1/2}),$$

are continuous linear mappings, and so are

$$\mathcal{R} : \mathcal{E}'(X, \Omega_X^{1/2}) \rightarrow \mathcal{D}'(\mathcal{G}, \Omega_{\mathcal{G}}^{1/2}), \quad \mathcal{R}^* : \mathcal{E}'(\mathcal{G}, \Omega_{\mathcal{G}}^{1/2}) \rightarrow \mathcal{D}'(X, \Omega_X^{1/2}).$$

More precisely  $\mathcal{R}$  and  $\mathcal{R}^*$  are elliptic Fourier integral operators.

## Mapping properties of double fibration transforms

**Theorem 3 ([3, Theorem 2.2] & [Hörmander IV, Theorem 25.2.2])**

Suppose that  $Z$  is a double fibration with  $\dim(Z) = N + n'$ . Then  $\mathcal{R}$  and  $\mathcal{R}^*$  are elliptic Fourier integral operators of order  $-(N + 2n' - n)/4$  with canonical relations  $(N^*Z \setminus 0)'$  and  $((N^*Z \setminus 0)^T)'$  respectively. More precisely

$$\begin{aligned}\mathcal{R} &\in \mathcal{I}^{-(N+2n'-n)/4}(\mathcal{G} \times X, N^*Z \setminus 0; \Omega_{\mathcal{G} \times X}^{1/2}), \\ \mathcal{R}^* &\in \mathcal{I}^{-(N+2n'-n)/4}(X \times \mathcal{G}, (N^*Z \setminus 0)^T; \Omega_{X \times \mathcal{G}}^{1/2}),\end{aligned}$$

where

$$\begin{aligned}N^*Z \setminus 0 &= \{(z, A(z, x)\eta, x, \eta) : (z, x) \in Z, \eta \in N_x^*G_z \setminus \{0\}\} \\ &= \{(z, \zeta, x, B(z, x)\zeta) : (z, x) \in Z, \zeta \in N_z^*H_x \setminus \{0\}\},\end{aligned}$$

$A(z, x) \in \text{Hom}(N_x^*G_z, T_z^*\mathcal{G})$  and  $B(z, x) \in \text{Hom}(N_z^*H_x, T_x^*X)$  smoothly depend on  $(z, x) \in Z$  respectively.

## Examples of double fibration transforms

- **$d$ -plane transform on  $\mathbb{R}^n$ :**  $\mathcal{G} := G(d, m)$ ,  $X := \mathbb{R}^n$ .
- **Geodesic X-ray transform:** Let  $(M, g)$  be a compact and nontrapping Riemannian manifold with a strictly convex boundary. Denote by  $\nu(x)$  the unit outer normal vector at  $x \in \partial M$ . Then

$$\mathcal{G} := \partial_- SM = \{(x, u) \in SM : x \in \partial M, \langle u, \nu(x) \rangle < 0\}, \quad X := M^{\text{int}}.$$

- **Null bicharacteristics:** Let  $P$  be a real-principal-type pseudodifferential operator on a manifold  $X$  with the principal symbol  $p_m(x, \xi)$ . Let  $\mathcal{G}$  be the set of all Hamilton flows for  $p_m(x, \xi) = 0$  on  $T^*X$ , and consider the integration over all the  $\gamma \in \mathcal{G}$ .
- **Light ray transform:** This is a special case of the above. Let  $(M, g)$  be a Lorentzian manifold, and set  $P$  be the d'Alembertian.

## *Z*-conjugate points

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For local coordinates  $(z, x) = (z', z'', x', x'') \in \mathbb{R}^{N-n''} \times \mathbb{R}^{n''} \times \mathbb{R}^{n'} \times \mathbb{R}^{n''}$ , There exist  $\mathbb{R}^{n''}$ -valued functions  $\phi(z, x')$  and  $b(x, z')$  such that we have locally

$$Z = \{x'' = \phi(z, x')\} = \{z'' = b(x, z')\}.$$

### Lemma 4 ([3, Lemmas 2.4, 2.5 and 2.6])

$$N_{(z,x)}^* Z = \left\{ \left( -\phi_z(z, x')^T \eta'', (-\phi_{x'}(z, x')^T \eta'', \eta'') \right) : \eta'' \in \mathbb{R}^{n''} \right\},$$

$$A(z, x) \begin{bmatrix} -\phi_{x'}(z, x')^T \\ I_{n''} \end{bmatrix} \eta'' = -\phi_z(z, x')^T \eta'', \quad \eta'' \in \mathbb{R}^{n''}.$$

Similar results hold for  $b(x, z')$  and  $B(z, x)$ .

## Variation fields and conjugate points

Fix arbitrary  $(z, w) \in T\mathcal{G}$ , and consider a curve in  $\mathcal{G}$  of the form

$$z(s) = z + sw + \mathcal{O}(s^2) \quad \text{near } s = 0.$$

Then  $(G_{z(s)})$  is said to be a variation of  $G_z$ , and the variation field  $J_w : G_z \rightarrow (N_x^* G_z)^*$  associated to  $(G_{z(s)})$  is defined by

$$J_w(x) := A(z, x)^* w \simeq -\phi_z(z, x') w \in (N_x^* G_z)^* \simeq N_x G_z = T_x X / T_x G_z$$

for  $x \in G_z$ . Note that  $T_z H_x = \text{Ker}(A(z, x)^*)$  since  $\phi(z(s), x') = x''$  for  $z(s) \in H_x$ , and

$$A(z, x)^* \in \text{Hom}(T_z \mathcal{G}, (N_x^* G_z)^*) \simeq \text{Hom}(T_z \mathcal{G}, N_x G_z), \quad (z, x) \in Z,$$

For  $z \in \mathcal{G}$  and  $x, y \in G_z$ , set

$$V_z(x, y) := \{J_w(x) : w \in T_z \mathcal{G}, J_w(y) = 0\}.$$

Note that  $\dim(V_z(x, y)) \leq n''$  holds since  $\text{rank}(A(z, x)^*) = n''$ , and  $\dim(V_z(x, y)) = \dim(V_z(y, x))$  holds for any  $z \in \mathcal{G}$  and  $x, y \in G_z$ .

cf. If  $x = \exp_y(tu)$ , then  $J_w(x) \simeq Y(t) := tD\exp_y(tu)w$ .

## $Z$ -conjugate triplets

### Definition 5

Suppose that  $Z$  is a double fibration and  $N \geq 2n''$ . Let  $k = 1, \dots, n''$ .

- **$Z$ -conjugate triplet of degree  $k$ :** Let  $z \in \mathcal{G}$  and let  $x, y \in G_z$  with  $x \neq y$ . We say that  $(z; x, y)$  is a  $Z$ -conjugate triplet of degree  $k$  if  $\dim(V_z(x, y)) = n'' - k$ .
- **Regular  $Z$ -conjugate triplet of degree  $k$ :** We say that a  $Z$ -conjugate triplet  $(z; x, y)$  of degree  $k$  is regular if there exist a nbd  $U_x$  of  $x$  in  $X$ , a nbd  $U_y$  of  $y$  in  $X$ , and a nbd  $W_z$  of  $z$  in  $\mathcal{G}$  such that any  $Z$ -conjugate triplet  $(z'; x', y') \in W_z \times U_x \times U_y$  is also of degree  $k$ . The set of all the regular  $Z$ -conjugate triplets of degree  $k$  is denoted by  $C_{R,k}$ .
- The set of all the  $Z$ -conjugate triplets which are not regular is denoted by  $C_S$ .

## How to describe $Z$ -conjugacy 1/2

Let  $(z_0; x_0, y_0)$  be a  $Z$ -conjugate triplet of degree  $k = 1, \dots, n''$ .  $Z$  is locally expressed by  $\phi$  and  $\psi$  as  $\{x'' = \phi(z, x')\}$  near  $(z_0, x_0)$  and  $\{y'' = \psi(z, y')\}$  near  $(z_0, y_0)$  respectively, and

$$V_{z_0}(x_0, y_0) = \{\phi_z(z_0, x'_0)w : w \in \text{Ker}(\psi_z(z_0, y'_0))\}.$$

Set  $\phi = [\phi^{(1)}, \dots, \phi^{(n'')}]^T$  and  $\psi = [\psi^{(1)}, \dots, \psi^{(n'')}]^T$ . Then  $\{\phi_z^{(1)}, \dots, \phi_z^{(n'')}\}$  and  $\{\psi_z^{(1)}, \dots, \psi_z^{(n'')}\}$  are linearly independent near  $(z_0, x_0)$  and  $(z_0, y_0)$  respectively. Note that

$$\text{Ker}(\psi_z(z_0, y'_0)) = \text{span}\langle \psi_z^{(1)}(z_0, y'_0)^T, \dots, \psi_z^{(n'')}(z_0, y'_0)^T \rangle^\perp \quad \text{in } \mathbb{R}^N.$$

We deduce that  $\dim(V_{z_0}(x_0, y_0)) = n'' - k$  is equivalent to

$$\dim\left(\text{span}\langle \phi_z^{(1)}(z_0, x'_0), \dots, \phi_z^{(n'')}(z_0, x'_0) \rangle \cap \text{span}\langle \psi_z^{(1)}(z_0, y'_0), \dots, \psi_z^{(n'')}(z_0, y'_0) \rangle\right) = k. \quad (1)$$

We express (1) by  $k$  equations.

## How to describe $Z$ -conjugacy 2/2

Denote by  $\{\tilde{\psi}_z^{(1)}, \dots, \tilde{\psi}_z^{(n'')}\}$  the Schmidt orthonormalization of  $\{\psi_z^{(1)}, \dots, \psi_z^{(n'')}\}$ .

(1) is equivalent to the following: there exist  $\lambda_1, \dots, \lambda_k \in \mathbb{R}^{n''}$ ,  $\lambda_I = [\lambda_{I1}, \dots, \lambda_{In''}]$  ( $I = 1, \dots, k$ ) such that  $\lambda_1, \dots, \lambda_k$  are linearly independent and if we set

$$\phi_z^{\lambda_I}(z, x') := \lambda_I \phi_z(z, x') = \sum_{m=1}^{n''} \lambda_{Im} \phi_z^{(m)}(z, x'),$$

$$\begin{aligned} H^{\lambda_I}(z, x', y') &:= \phi_z^{\lambda_I}(z, x') \phi_z^{\lambda_I}(z, x')^T - \sum_{m=1}^{n''} |\phi_z^{\lambda_I}(z, x') \tilde{\psi}_z^{(m)}(z, y')^T|^2 \\ &= \lambda_I \phi_z(z, x') (I_N - \tilde{\psi}_z^T(z, y') \tilde{\psi}_z(z, y')) \phi_z(z, x')^T \lambda_I^T, \end{aligned}$$

$$H^\lambda(z, x', y') := [H^{\lambda_1}(z, x', y'), \dots, H^{\lambda_k}(z, x', y')]^T,$$

for  $I = 1, \dots, k$ , then

$$H^\lambda(z_0, x'_0, y'_0) = 0. \tag{2}$$

## An artificial condition (H)

**Condition (H):** Let  $k = 1, \dots, n''$ . Suppose that  $(z_0; x_0, y_0) \in C_{R,k}$ . Suppose that  $H^\lambda(z, x', y')$  is the same as that of the previous paragraph and satisfies (2).

Condition (H) is that  $\text{rank}(D_{z,x',y'} H^\lambda(z_0, x'_0, y'_0)) = 1$  holds for any choice of linearly independent  $\lambda_1, \dots, \lambda_k \in \mathbb{R}^{n''}$ .

### Spirit of Condition (H):

- **rank one:** We refer the case of the geodesic X-ray transform for the dimension. In other words we fit our case to the geodesic X-ray transform.
- **for any choice of  $\lambda_1, \dots, \lambda_k$ :** We avoid the case that there exist two choices  $\lambda_1, \dots, \lambda_k$  and  $\lambda'_1, \dots, \lambda'_k$  such that

$$\{H^\lambda(z, x', y') = 1\} \cap \{H^{\lambda'}(z, x', y') = 1\}$$

is transversal.

**Lemma 6**

Suppose that  $Z$  is a double fibration,  $N \geq 2n''$  and some condition (H). For any  $k = 1, \dots, n''$ ,  $C_{R,k}$  is an  $(N + 2n' - 1)$ -dimensional embedded submanifold of  $\mathcal{G} \times X \times X$ .

Note that the connected component of  $C_{R,k}$  containing  $(z_0; x_0, y_0)$  is characterized by

$$F(x'', y'', z; x', y') := \begin{bmatrix} x'' - \phi(z, x') \\ y'' - \psi(z, y') \\ H^\lambda(z, x', y') \end{bmatrix} = 0 \quad \text{near } (z_0; x_0, y_0).$$

We have

$$\text{rank}(DF(x_0'', y_0'', z_0; x_0', y_0')) = \text{rank} \begin{bmatrix} I_{n''} & O & * \\ O & I_{n''} & * \\ O & O & D_{z,x',y'} H^\lambda(z_0, x_0', y_0') \end{bmatrix} = 2n'' + 1.$$

## Structure of normal operators

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# Normal operators without $Z$ -conjugate points

$$\mathcal{R}^* \mathcal{R} f(x) = \left( \iint_{H_x \times G_z} \overline{\kappa(z, x)} \kappa(z, y) \frac{f}{|dX|^{1/2}}(y) dG_z(y) dH_x(z) \right) |dX(x)|^{1/2}, \quad x \in X.$$

Set  $\mathcal{C} := (N^* Z \setminus 0)'$ , which is the canonical relation of  $\mathcal{R}$ .

## Theorem 7

Suppose that  $Z$  is a double fibration. In addition, we assume  $N \geq 2n''$  and the following:

- $\pi_X : Z \rightarrow X$  is proper, and  $\pi_X^{-1}(x)$  is connected for any  $x \in X$ .
- There are no  $Z$ -conjugate triplets, and  $D\pi_L$  is injective at all  $(z, \zeta, x, \eta) \in \mathcal{C}$ .

Then  $\mathcal{C}^T \circ \mathcal{C}$  is a clean intersection with excess  $e = N - n$ , and  $\mathcal{R}^* \mathcal{R}$  is an elliptic pseudodifferential operator of order  $-n'$  on  $X$ .

Proof: Some lemmas in [3] and the assumptions guarantee the Bolker condition.  $\square$

## Known results on geodesic X-ray transforms with conjugate points

- Let  $(M, g)$  be a compact Riemannian manifold with strictly convex boundary. Set  $\gamma_w(t) := \exp_{\pi_M(w)}(tw)$  for  $w \in \partial_-SM$ . Consider the geodesic X-ray transform
$$\mathcal{X}f(w) := \left( \int_0^{\tau(w)} \kappa(\gamma_w(t), \dot{\gamma}_w(t)) \frac{f}{|dM|^{1/2}}(\gamma_w(t)) dt \right) |d\partial_-SM(w)|^{1/2}.$$
- Stefanov and Uhlmann (2012) [4]: If  $v_0 = |v_0|\theta_0$  is a fold conjugate vector at  $p_0$ , and  $v_0$  is the only singularity of  $\exp_{p_0}(v)$  on  $\gamma_{\theta_0}$  near  $p_0$ , then the localized normal operator is decomposed as

$$\mathcal{X}^* \chi \mathcal{X} = A + F \quad \text{near } p_0,$$

where  $A$  is a PsDOs of order  $-1$ , and  $F$  is a  $FIO$  of order  $-n/2$ .

- Holman and Uhlmann (2018) [2]: If  $C_S = \emptyset$ , then

$$\mathcal{X}^* \mathcal{X} = A + \sum_{k=1}^{n-1} \sum_{\alpha=1}^{M_k} F_{k,\alpha},$$

where  $A$  is a PsDOs of order  $-1$ , and  $F$  is a  $FIO$  of order  $-(n - k + 1)/2$ .

# Normal operators with $Z$ -conjugate points

## Theorem 8

Suppose that  $Z$  is a double fibration,  $C_S = \emptyset$ ,  $N \geq 2n''$ , condition (H) and the following:

- $\pi_X$  is proper, and  $\pi_X^{-1}(x)$  is connected for any  $x \in X$ .
- If  $\pi_L^{-1}((z, \zeta)) = \{(z, \zeta, x, \eta)\}$  for  $(z, \zeta, x, \eta) \in \mathcal{C}$ , then  $D\pi_L|_{(z, \zeta, x, \eta)}$  is injective.

Then we have a decomposition of  $\mathcal{R}^* \mathcal{R}$  of the form

$$\mathcal{R}^* \mathcal{R} = A + \sum_{k=1}^{n''} \sum_{\alpha \in \Lambda_k} F_{k,\alpha},$$

where  $A$  is an elliptic PsDO of order  $-n'$  on  $X$ ,

$F_{k,\alpha}$  is a FIO in  $\mathcal{I}^{-(n+1-k)/2}(X \times X, \mathcal{C}'_{A_{k,\alpha}}; \Omega_{X \times X}^{1/2})$  with some canonical relation of  $\mathcal{C}_{F_{k,\alpha}}$ , associated to the decomposition of connected components  $C_{R,k} = \bigcup_{\alpha \in \Lambda_k} C_{R,k,\alpha}$ .

## Outline of the proof

- $\mathcal{R}^*\mathcal{R}$  is given by

$$\frac{\mathcal{R}^*\mathcal{R}f}{|dX|^{1/2}}(x) = \iint_{H_x \times G_z} \overline{\kappa(z, x)} \kappa(z, y) \frac{f}{|dX|^{1/2}}(y) dG_z(y) dH_x(z).$$

- Follow the idea of Holman and Uhlmann [2]: a partition of unity of  $\mathcal{G} \times X \times X$ .
- Set  $C_\delta := \{(z; x, x) : z \in \mathcal{G}, x \in X\}$ , which is related to the elliptic term.
- $C_{R,k,\alpha}$  are disjoint since  $C_S = \emptyset$ , so are  $C_{R,k,\alpha}$  and  $C_\delta$ .  
Pick up disjoint nbds  $U_{k,\alpha}$  and  $U_\delta$  of  $C_{R,k,\alpha}$  and  $C_\delta$  respectively in  $\mathcal{G} \times X \times X$ .
- We can find an open set  $U_0$  in  $\mathcal{G} \times X \times X$  such that

$$U_0 \bigcup U_\delta \bigcup (\cup U_{k,\alpha}) = \mathcal{G} \times X \times X, \quad U_0 \cap (C_\delta \bigcup (\cup C_{R,k,\alpha})) = \emptyset.$$

- Pick up a partition of unity subordinated to  $\{U_0, U_\delta, U_{k,\alpha}\}$ , and split the Schwartz kernel of  $\mathcal{R}^*\mathcal{R}$ .  $U_0$ -part of  $\mathcal{R}^*\mathcal{R}$  is a smoothing operator, and is absorbed in  $U_\delta$ -part  $A$ .

## References

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